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IMPACT OF PREDICTION ACCURACY ON COSTS-NOISE TECHNOLOGY APPLICATIONS IN HELICOPTERS

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16. Abstract

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Although the number of helicopters studied is too small to permit generally applicable conclusions the following are the primary results:

The Effective Perceived Noise Levels tended to be overpredicted for takeoffs, underpredicted for approaches, with no general trend noted for level flyovers.

Prediction accuracy for the cases studied ranged from 1 to 6 EPNdB.

Test and measurement repeatability can give a range of up to 3 EPNdB.

Each helicopter must be studied as an individual case and generalization of cost trends should be avoided.

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METRIC CONVERSION FACTORS

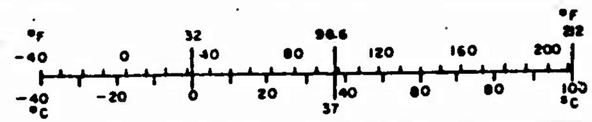
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

ILLUSTRATIONS

SYMBOLS

EPNL	-	Effective Perceived Noise Level
ISO	-	International Standards Organization
PNL	-	Perceived Noise Level
PNLT	-	Tone Corrected Perceived Noise Level
PNLTM	-	Maximum Tone Corrected Perceived Noise Level

I - SUMMARY

This study is an extension of the work reported in Reference 1, "A Study of Cost/Benefit Tradeoffs Available in Helicopter Noise Technology Applications", and considers the effect which uncertainties in the prediction and measurement of helicopter noise have on the development and operating costs.

Although the number of helicopters studied is too small to permit generally applicable conclusions the following are the primary results:

- The Effective Perceived Noise Levels tended to be overpredicted for takeoffs, underpredicted for approaches, with no general trend noted for level flyovers.
- Prediction accuracy for the cases studied ranged from 1 to 6 EPNdB.
- Test and measurement repeatability can give a range of up to 3 EPNdB.

Each helicopter must be studied as an individual case and generalization of cost trends should be avoided.

II - INTRODUCTION

The Reference 1 report assessed the impact of designing helicopters to noise constraints on the operating and acquisition cost of four helicopters. If the noise target is a guarantee, or a regulatory limit it is then necessary to set a design target level which is below that of the limit in order to ensure compliance. The amount of this margin is a function of the accuracy of the analytical predictions along with estimates of data repeatability, and the risk one is willing to assume. The purpose of this study is to provide a basis for evaluating the prediction accuracy of currently available analytical methodology and, using the results of Reference 1, the cost penalties which will result from the required design conservatism.

III - COMPARISON OF MEASURED AND PREDICTED LEVELS

This study is based on comparison between predicted and measured noise levels in level flight, takeoff, and approach, of three of the helicopters which were evaluated in Reference 1. The BO-105, a small single rotor helicopter; the CH-47C, a large tandem rotor helicopter whose acoustical signature is dominated by impulsive rotor noise; and a modified version of the CH-47C in which rotor noise was substantially reduced.

The prediction procedures used in this report are the same as those employed in the Reference 1 study. The methods are those described in Reference 2 and are summarized in Appendix A.

The data for the CH-47C helicopter was measured by the FAA and is reported in Reference 3. The data for the modified CH-47 was measured by Boeing Vertol using procedures which comply with proposed FAA and ICAO regulations. The data for the BO-105 had been recorded at an earlier date and the flight conditions did not match FAA/ICAO procedures. The predictions, however, were for the flight conditions actually tested.

Analytical predictions of Tone Corrected Perceived Noise Level (PNLT) time histories and EPNL values are presented in Figures 1, 2, and 3 along with directly comparable measured data. The time histories were drawn from PNLT calculations which were done at two second intervals. These curves were then interpolated to obtain predicted PNLT at one half second intervals for the EPNL calculations. The measured data was analyzed at one half second intervals.

Table I provides a comparison of the calculated and measured Perceived Noise Level (PNL), Tone Corrected Perceived Noise Level (PNLT) and the tone and duration corrections for each aircraft and flight condition or near the point of maximum PNL on the centerline of the flight path. The differences between predicted and measured levels are presented in Figure 4. In general the resultant EPNL's appear to be overpredicted for takeoff and underpredicted for approach. The latter is probably due to difficulty in accounting for noise due to blade-vortex intersection during descent. A similar problem with prediction of tandem rotor blade-vortex interaction noise in level flight is evident in Figure 1 where, in the case of the CH-47C, the high measured levels on the

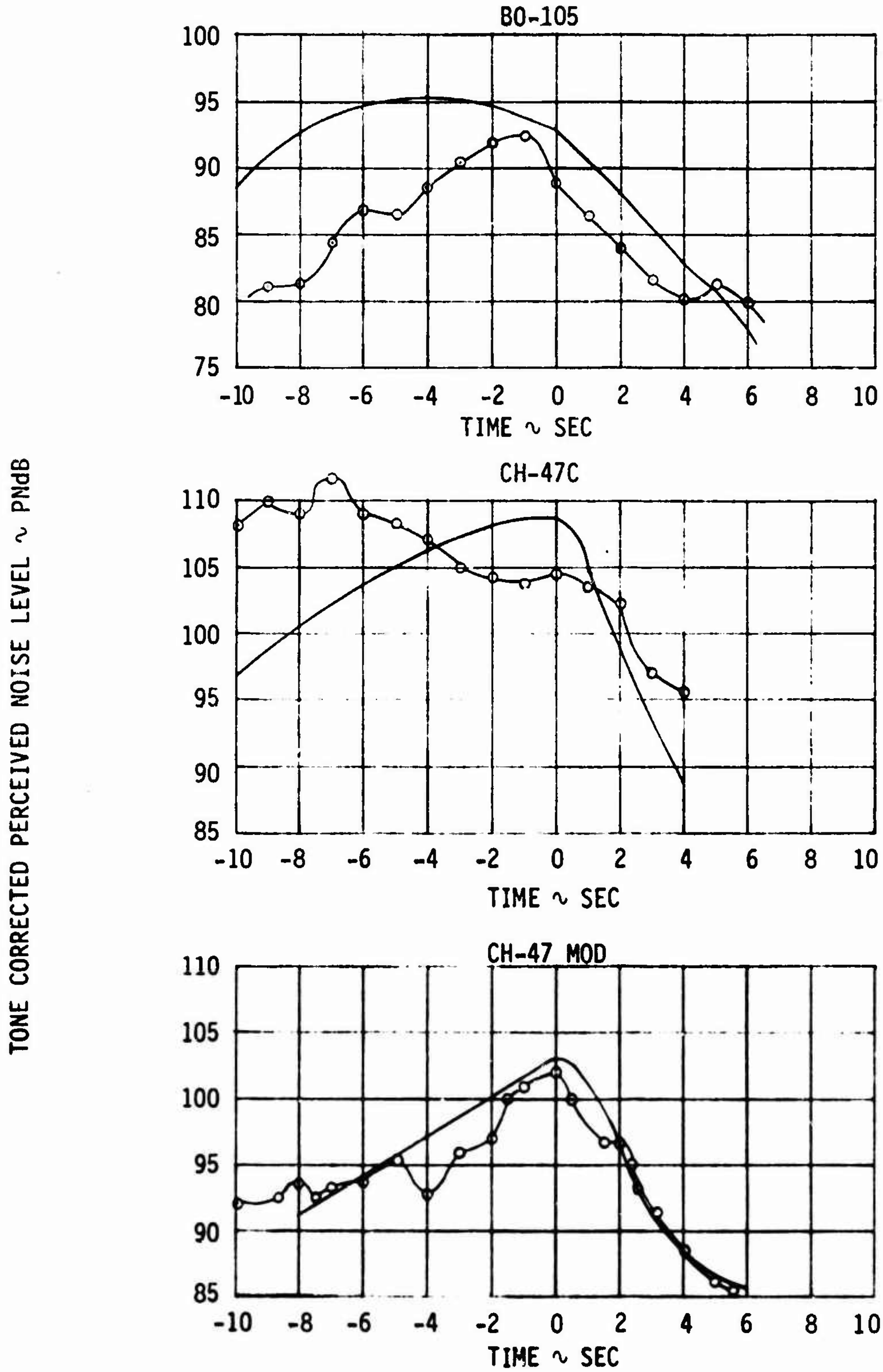


FIGURE 1. COMPARISON OF PREDICTED AND MEASURED PNLT TIME HISTORIES - FLYOVER

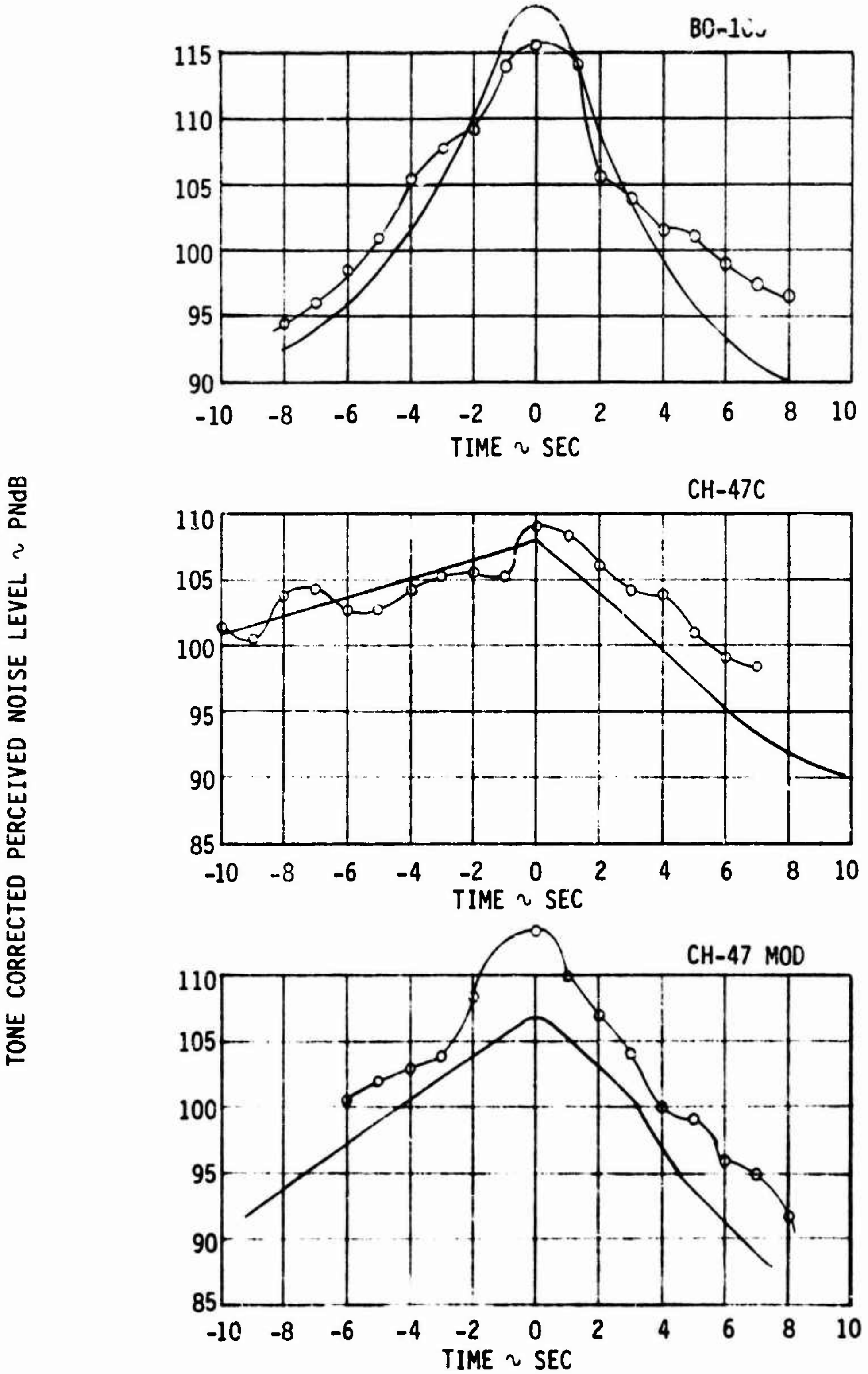


FIGURE 2. COMPARISON OF MEASURED AND PREDICTED PNLT TIME HISTORIES - APPROACH

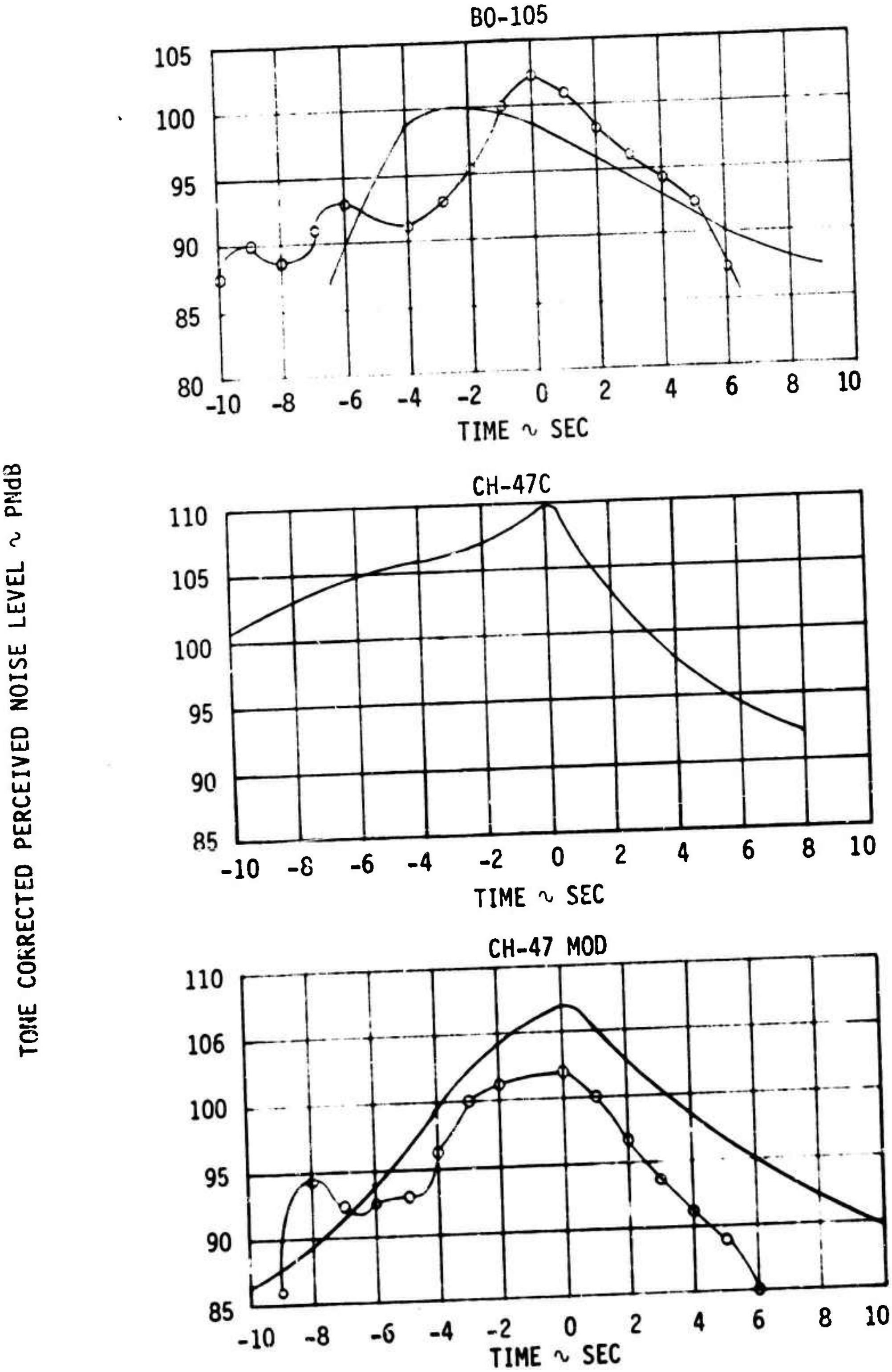


FIGURE 3. COMPARISON OF PREDICTED AND MEASURED PNLT TIME HISTORIES - TAKEOFF

TABLE I COMPARISON OF PREDICTIONS WITH MEASURED DATA

FLIGHT CONDITION	AIRCRAFT	PNL MAX		TONE CORRECTION		PNLTM		DURATION CORRECTION		EPNL	
		MEAS	PRED	MEAS	PRED	MEAS	PRED	MEAS	PRED	MEAS	PRED
APPROACH	BO-105	114.3	118.2	1.0	1.0	115.3	119.2	-5.1	-6.9	110.2	112.3
	CH-47C	107.9	107.4	0.7	0	108.6	107.4	-1.0	-0.8	107.6	106.6
	CH-47 Mod	111.9	106.5	1.0	0	112.9	106.5	-5.0	-3.3	107.9	103.2
FLYOVER	BO-105	89.2	92.8	3.3	1.0	92.5	93.8	-3.8	0.7	88.7	94.5
	CH-47C	104.6	108.7	0	0	104.6	108.7	4.3	-2.4	108.9	106.3
	CH-47 Mod	101.4	103.8	0.7	0	102.1	103.8	-4.4	-4.5	97.7	99.3
TAKEOFF	BO-105	99.8	96.3	2.2	0	102.0	96.3	-4.4	2.1	97.6	98.4
	CH-47C				NODATA						
	CH-47 Mod	101.2	107.0	0.9	0	102.1	107.0	-2.8	-3.8	99.3	103.2

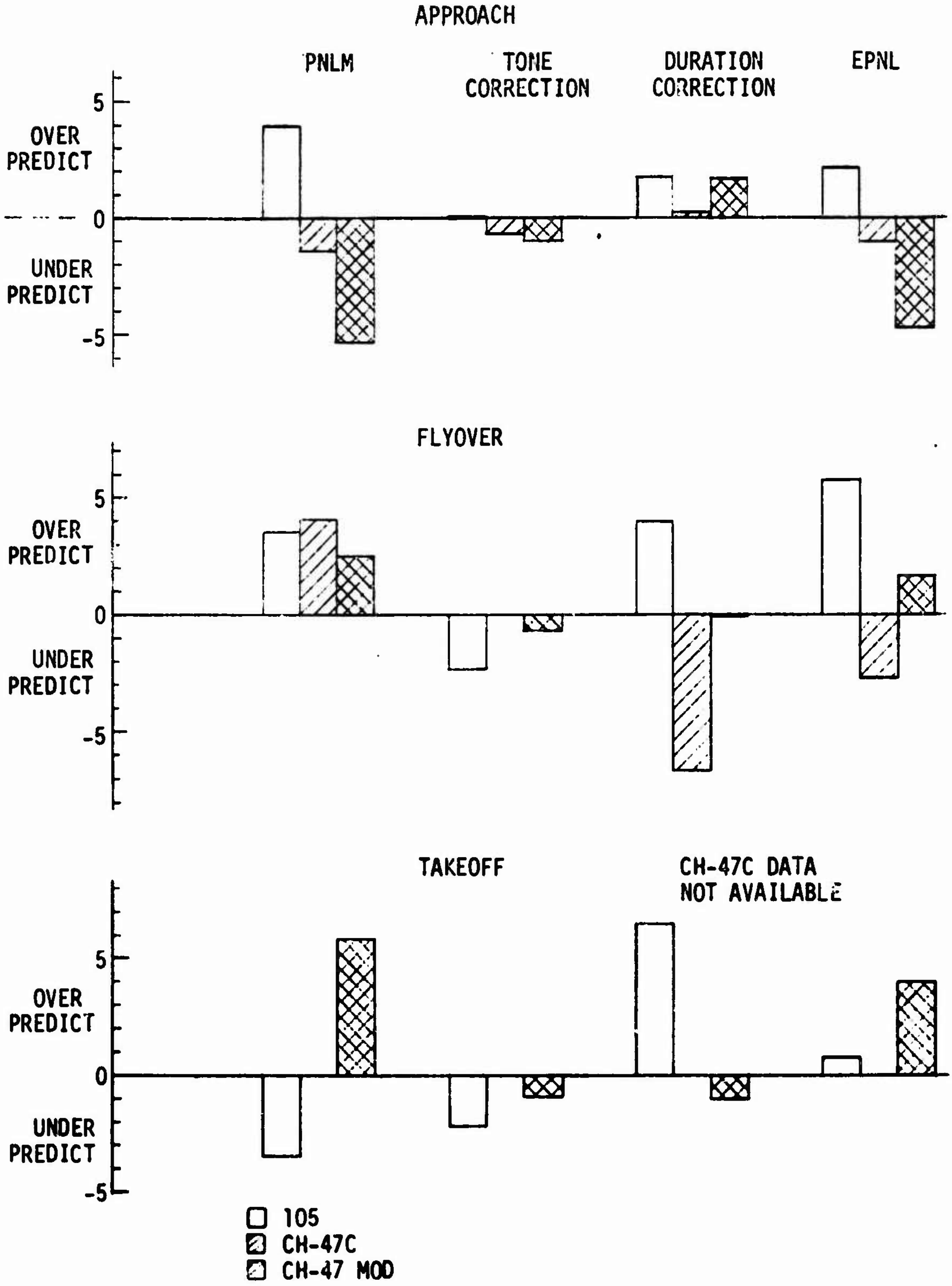


FIGURE 4. COMPARISON OF PREDICTED AND MEASURED DATA

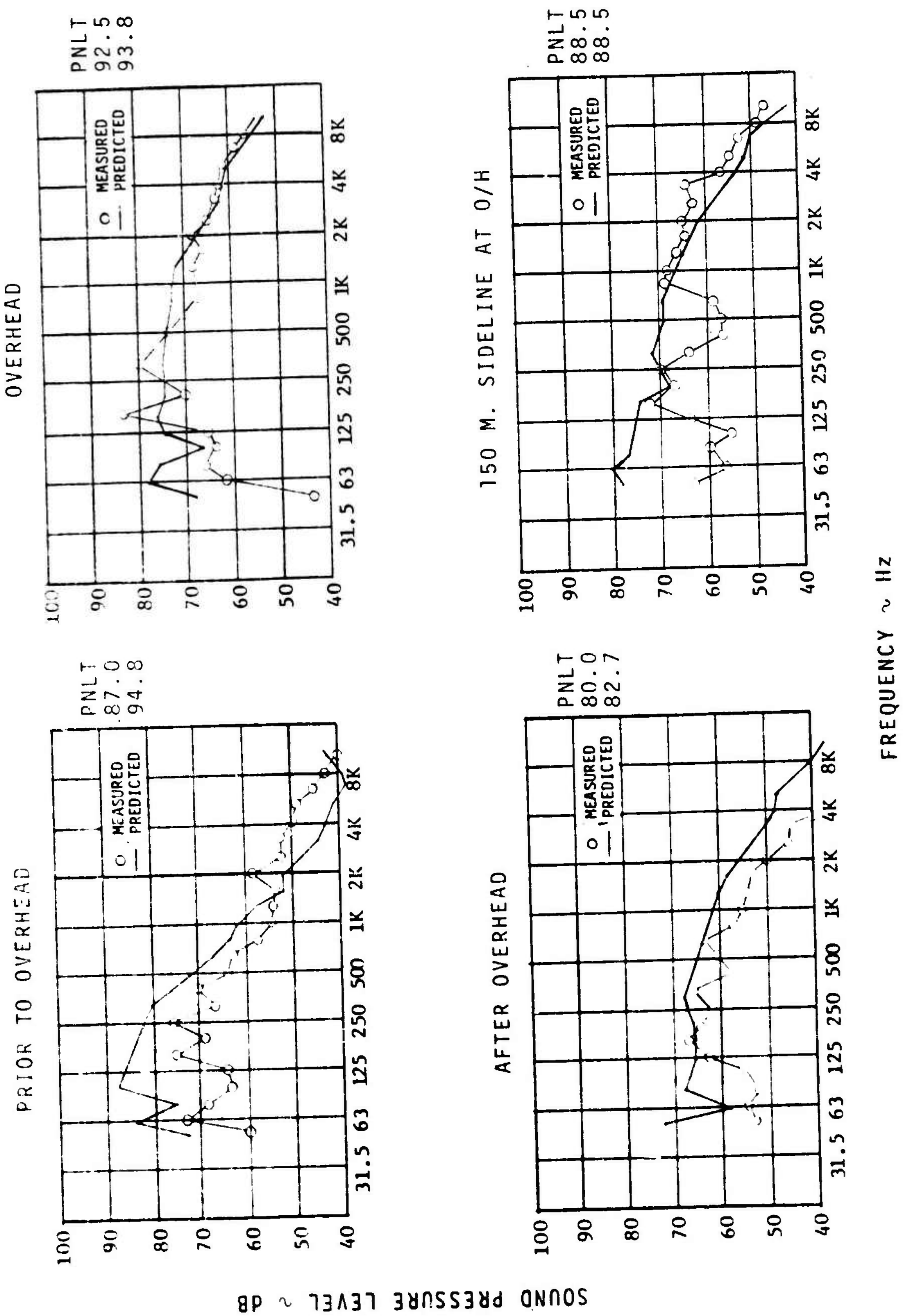


FIGURE 5. COMPARISON OF PREDICTED AND MEASURED SPECTRA, BO-105 FLYOVER

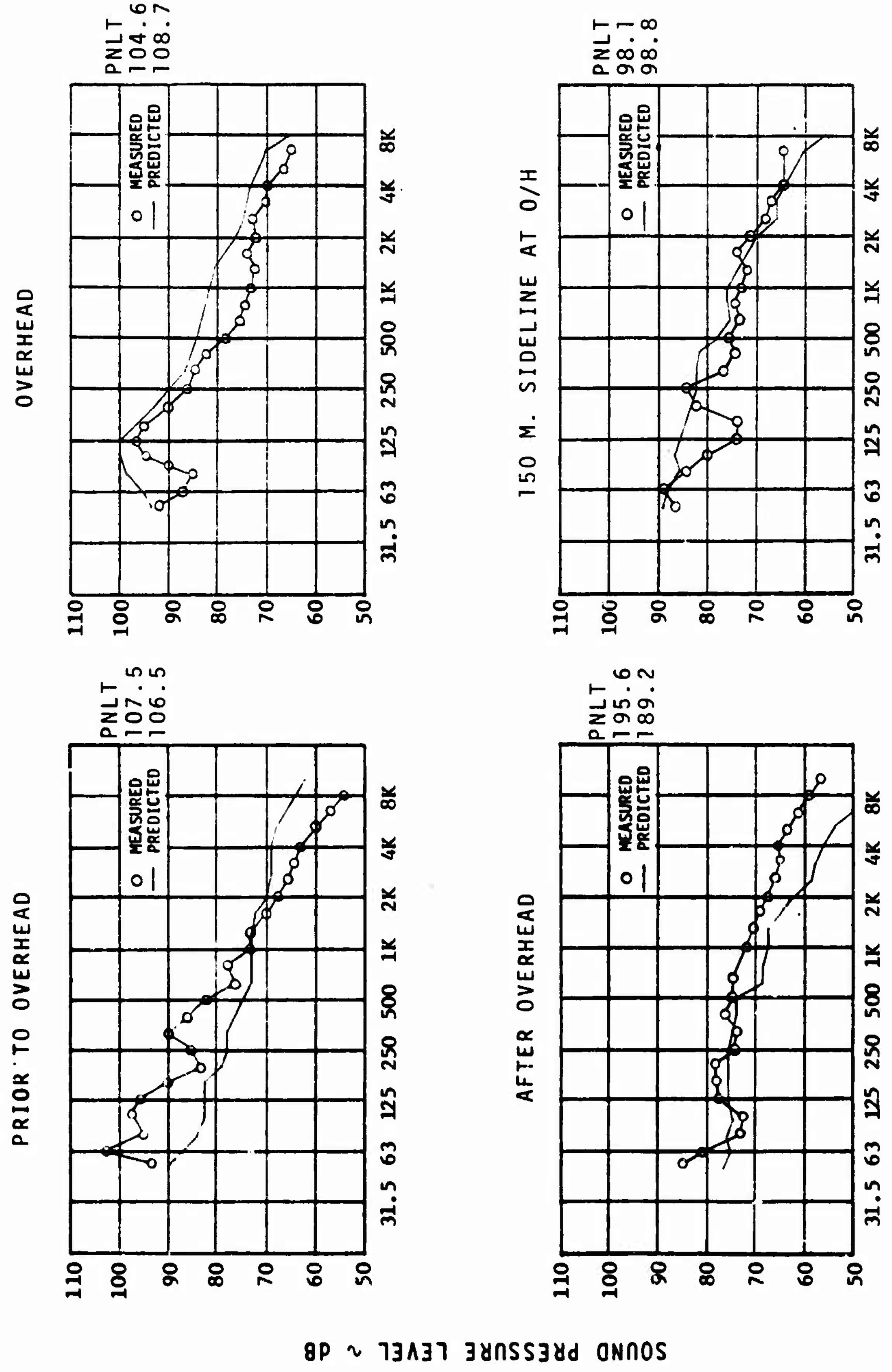


FIGURE 6. COMPARISON OF PREDICTED AND MEASURED SPECTRA, CH-47C FLYOVER

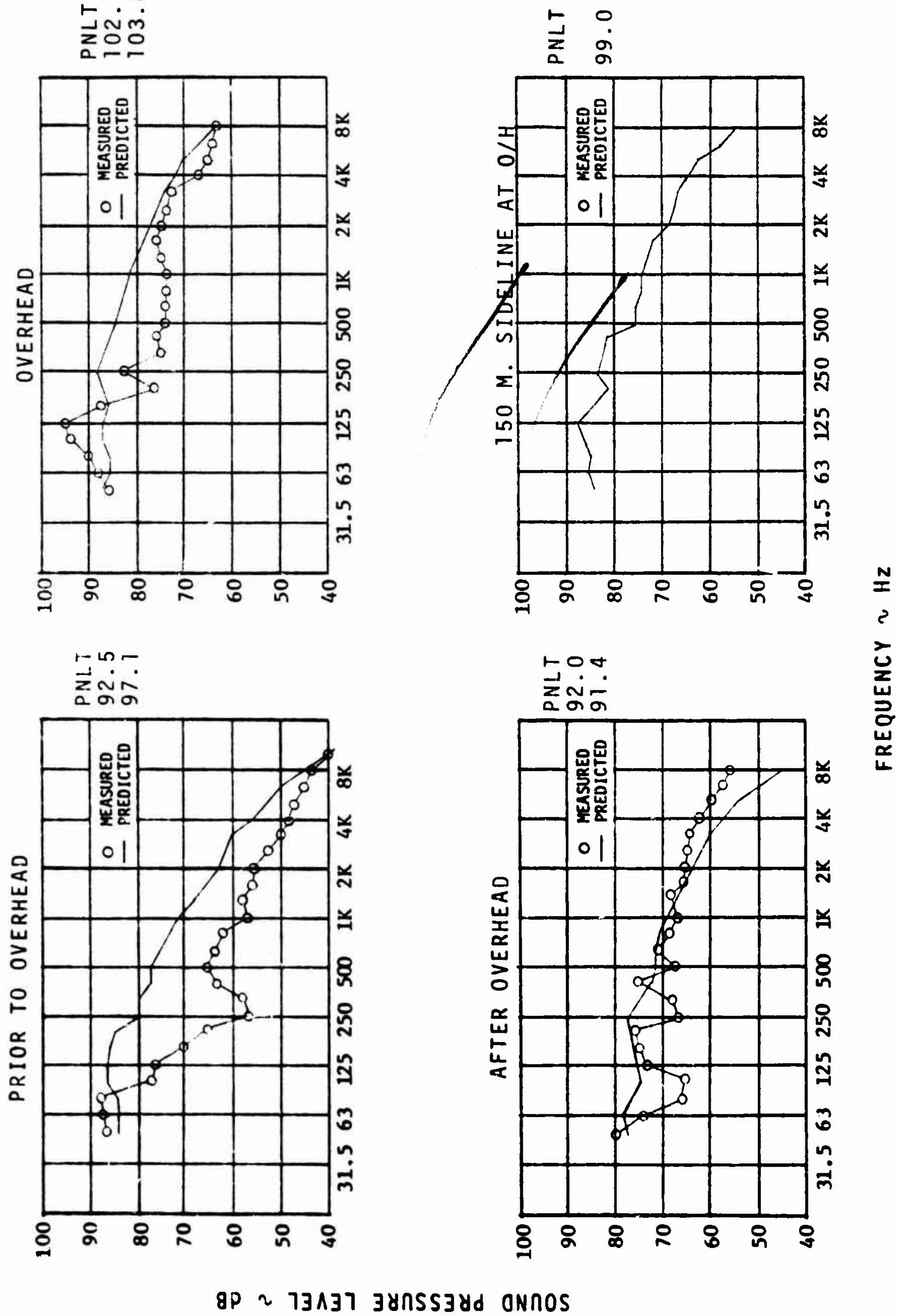


FIGURE 7. COMPARISON OF PREDICTED AND MEASURED SPECTRA, CH-47 MOD FLYOVER

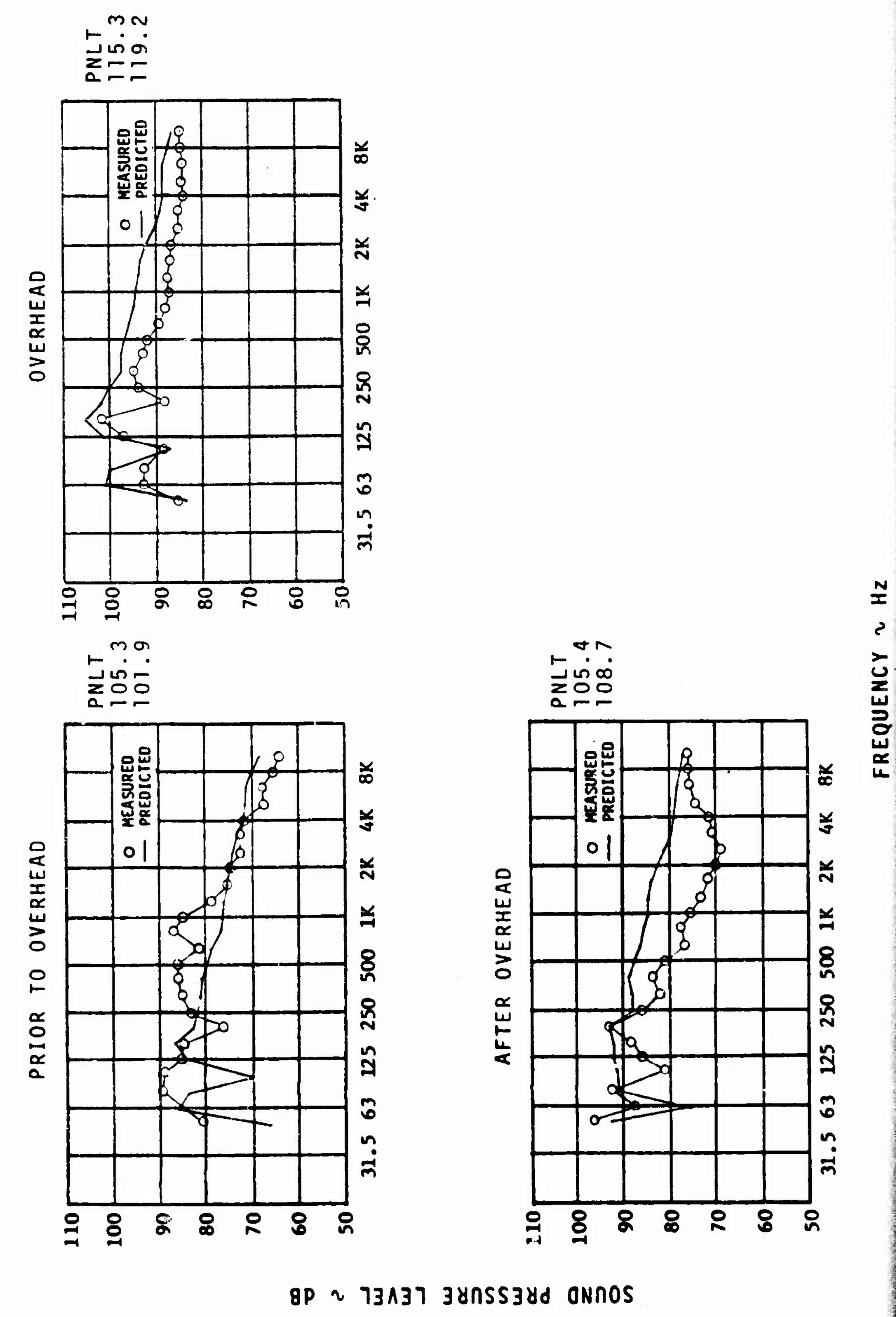


FIGURE 8. COMPARISON OF PREDICTED AND MEASURED SPECTRA, BO-105 APPROACH

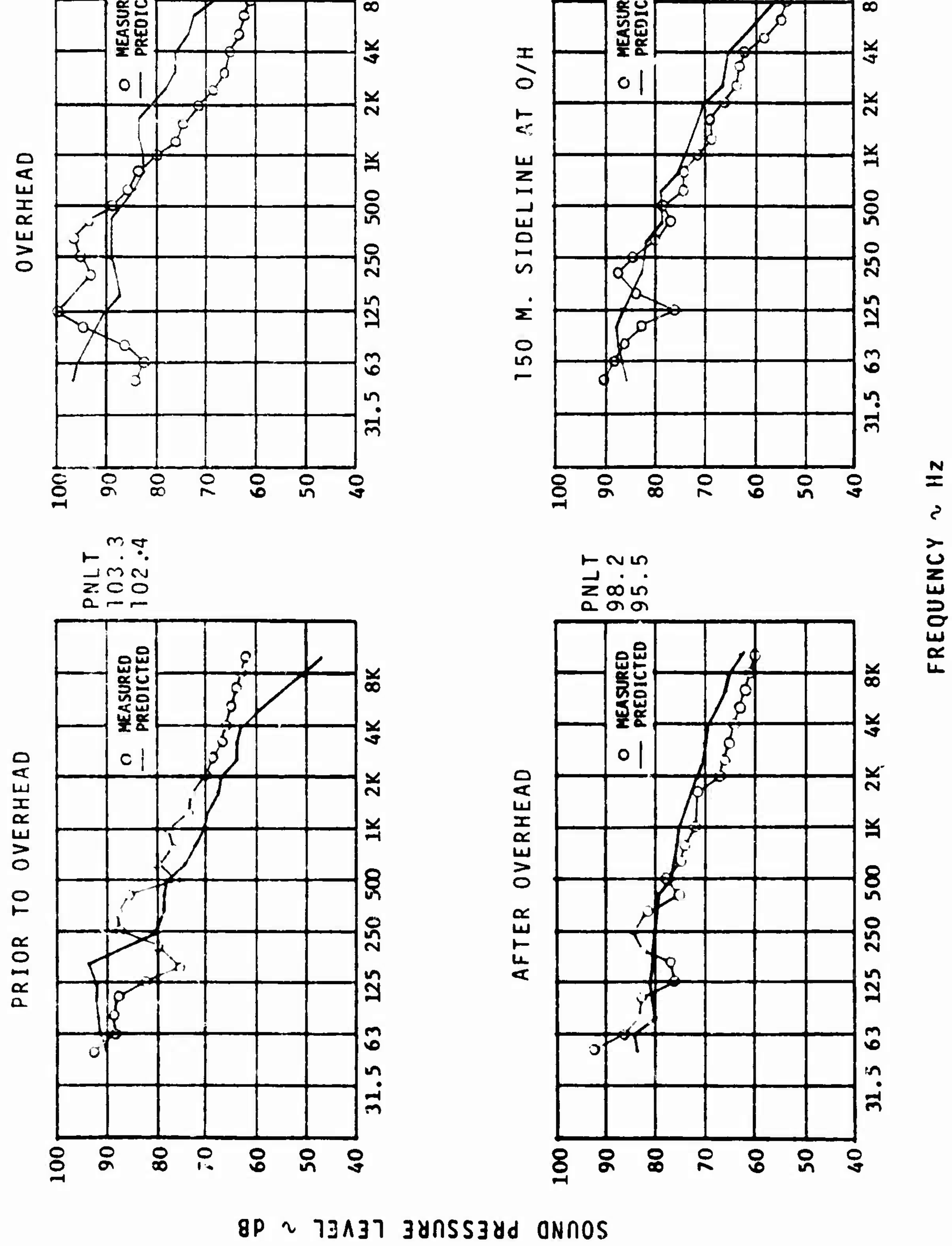


FIGURE 9. COMPARISON OF PREDICTED AND MEASURED SPECTRA, CH-47C APPROACH

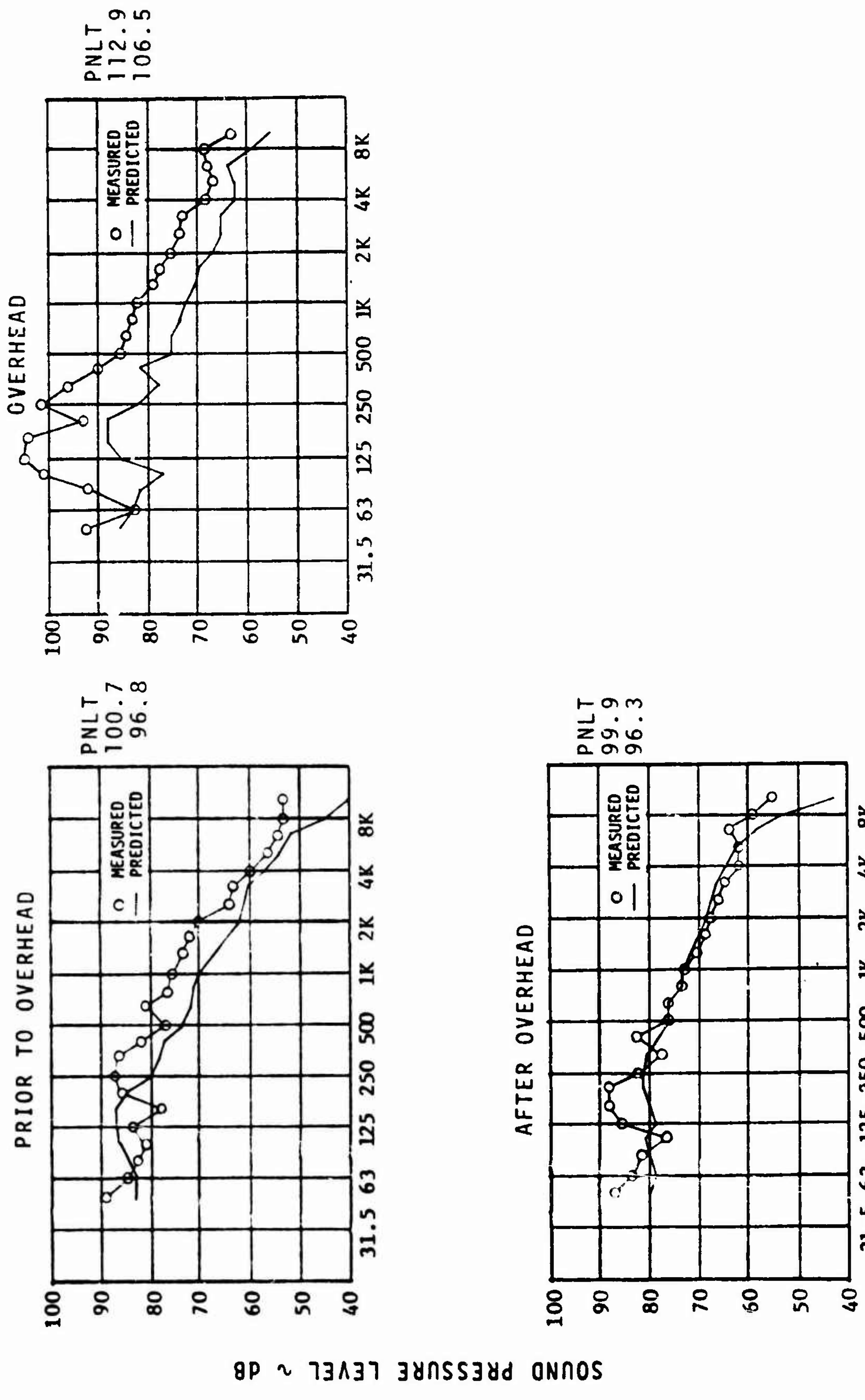


FIGURE 10. COMPARISON OF PREDICTED AND MEASURED SPECTRA, CH-47 MOD APPROACH

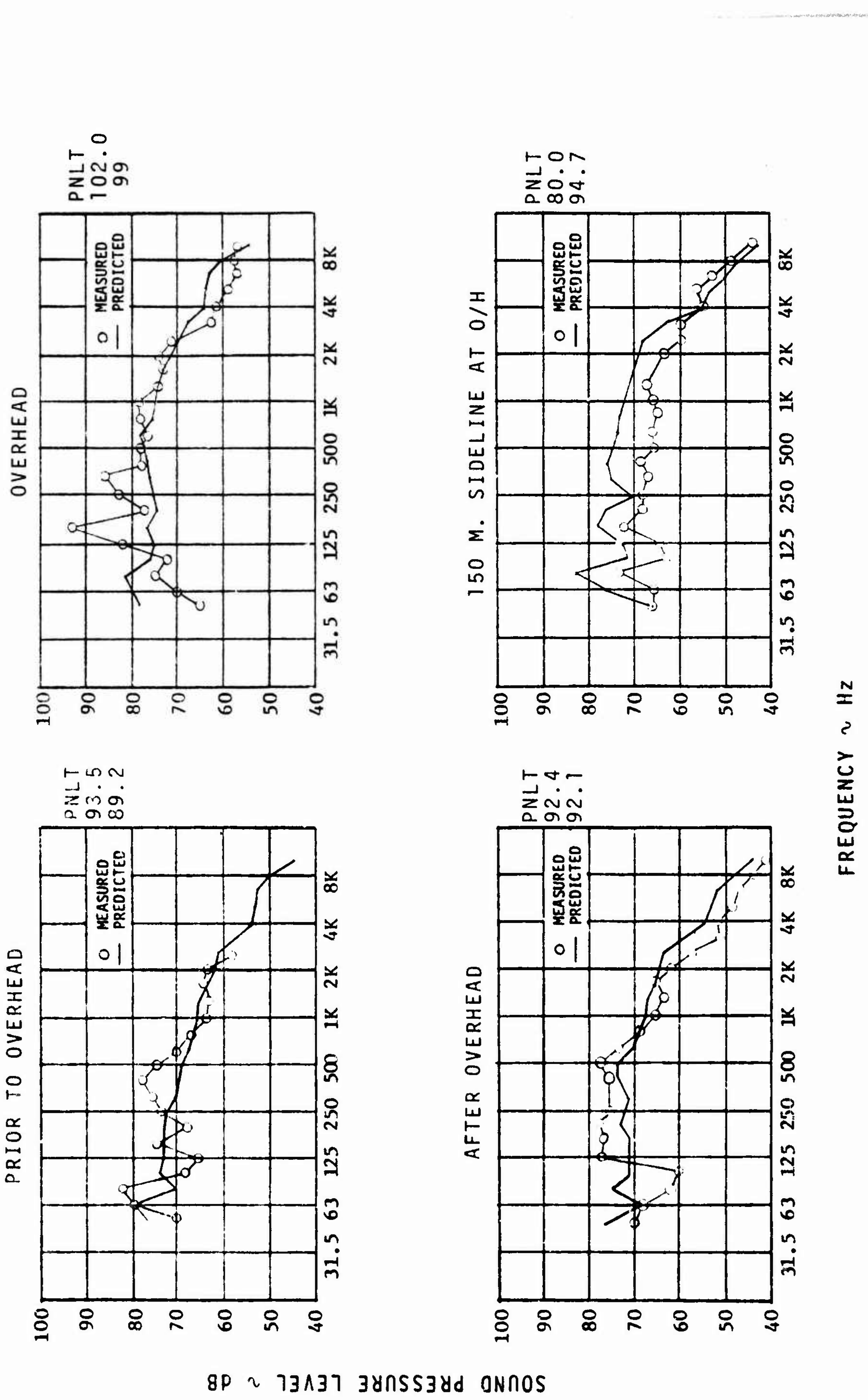


FIGURE 11. COMPARISON OF PREDICTED AND MEASURED SPECTRA, BO-105 TAKEOFF

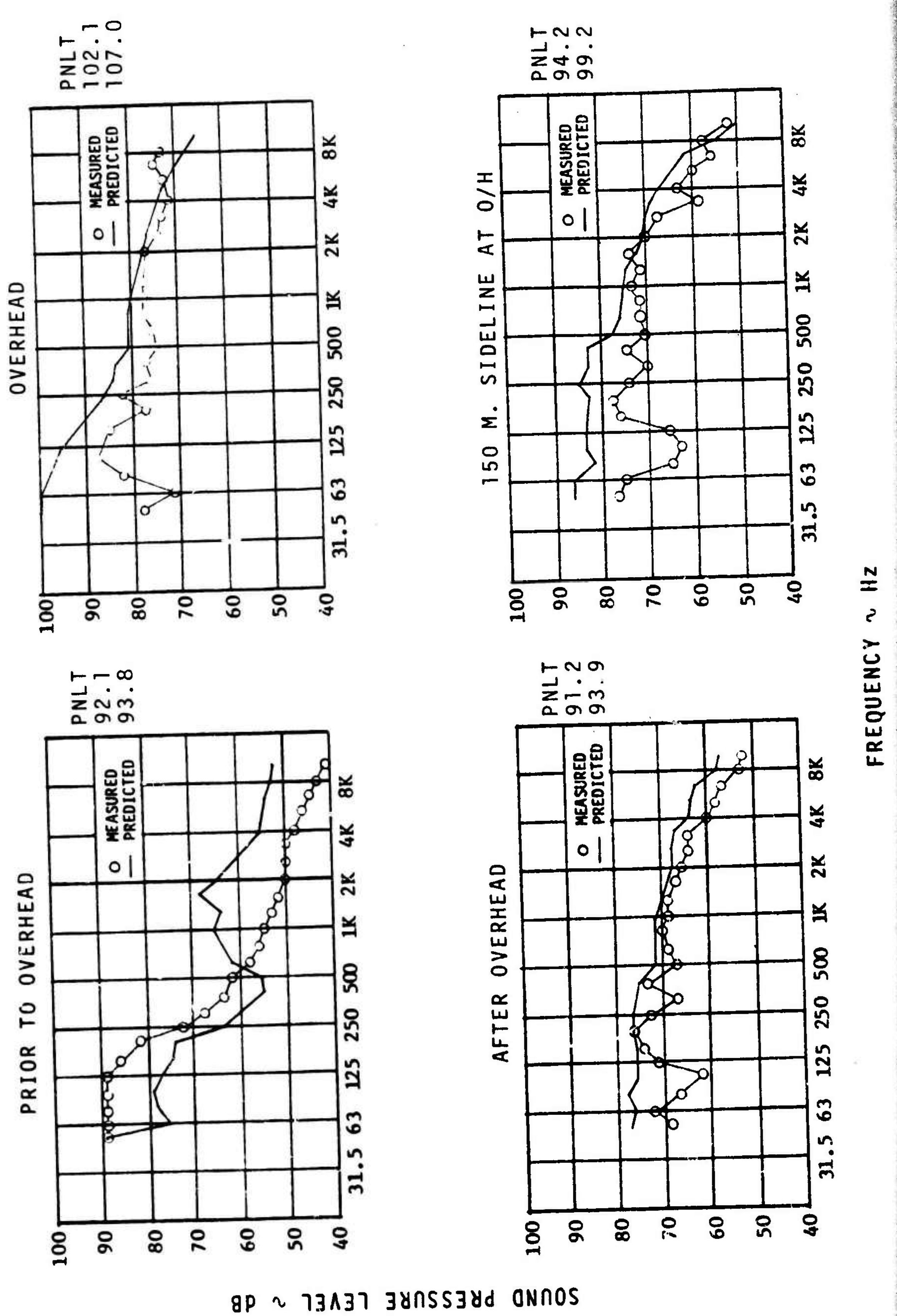


FIGURE 12. COMPARISON OF PREDICTED AND MEASURED SPECTRA, CH-47 MOD TAKEOFF

approach side are known to be impulsive noise which was eliminated on the CH-47 modified aircraft. Note that the prediction methodology which worked quite well for the non-impulsive modified version falls short when applied to the impulsive case.

Duration corrections appear to be very significant thereby indicating the importance of accurate prediction at points along the flight path other than at PNLTM. Tone corrections, although generally smaller than duration corrections appear to be consistently under-predicted. It is also interesting to note that larger tone corrections are applied to the single rotor BO-105 than to the tandem rotor configurations.

Spectra for each aircraft and flight condition are included in Figures 5-12. Comparisons are shown for three points under the centerline of the flight path and on the sideline at PNLTM. Although it is difficult to generalize these comparisons, it is apparent that the source of tone corrections is harmonic rotor noise below 500 Hz and that no corrections are evident due to high frequency engine noise.

IV - THE EFFECT OF MEASUREMENT VARIABLES ON THE ACCURACY OF DATA SAMPLES

The physical measurement of most engineering and scientific systems contains an element of scatter in the observed data, and the measurement of helicopter noise represents no exception. Aircraft position errors and operating condition variables, environmental conditions affecting noise generation, sound propagation factors data measurement and analysis techniques all influence the value of the data reported. The scatter thus generated results in a substantial uncertainty in the reported noise level for a given helicopter operating at a particular flight condition. For the noise certification of a helicopter the designers must recognize and deal with an inability to precisely predict the acoustical signature of the vehicle and to a lesser, but not inconsequential extent, the inability to accurately measure the noise level of that aircraft. The magnitude of the scatter resulting from these measurements influences the confidence that is assigned to the data, and ultimately the confidence in obtaining type certification of the helicopter itself.

Aircraft Flight Variables

The operation of a helicopter over a microphone range is subject to a number of variables which affect the magnitude of sound levels being generated. Included in these are airspeed, aircraft position (altitude, yaw, pitch and roll angles) rotor speed, and ambient temperature. While position errors may be corrected, factors which affect the fundamental generation of rotor noise are not accounted for by current procedures.

In addition, control system inputs (directional, collective and cyclic pitch variations) that stem from even moderately gusty conditions will result in undue transient noise from the rotor and once generated this becomes part of the helicopter noise signature.

Sound Propagation Variables

The transmission of sound from the helicopter to the microphone is strongly influenced by such factors as the air temperature, relative humidity, wind shear, ground surface variations and non-uniformity of ground cover. The adjustment of noise due to temperature and humidity effects is permitted, but not the remaining factors. Frequently the impact of these remaining elements varies seasonably and insufficient information is known regarding how each affects sound propagation.

Measurement

A third area which influences variability in helicopter noise measurements include microphone directivity characteristics, the dynamic range of the data system in use, orientation of the microphone during the measurement procedure and accuracy of measurement of aircraft position information with regard to acoustic data.

A fourth area affecting variability of helicopter noise measurement involves the instrumentation which is used for data analysis. Filter characteristics of the analyzer, while meeting ISO requirements, vary between manufacturers, and different analyzers will give different results for the same flyover. Variation in the start time of a data analysis record also will produce small variations in the EPNL values for a given flyover, and levels may vary by as much as 0.5 EPNdB for repeat analysis of the same record. In order to evaluate these variations in analysis by each investigation involved in aircraft noise certification, a common tape recording of aircraft or helicopter flyover noise is being circulated and analyzed. The results of these analysis are reported and the magnitude of the variation in data analysis assessed. These "Round-Robin" procedures are helpful to understand the variation in levels which exist due to analysis technique variations alone. Other "Round-Robin" tests should be conducted which include data acquisition as well as analysis.

All of the above notwithstanding, Paragraph H 36.105 of NPRM 79-13 (Ref. 4) and Paragraph A36.5 (e) (2) of FAR-36 (Ref. 5) specify that the maximum acceptable spread of data, for certification purposes is that which results in a 90% confidence limit of ± 1.5 EPNdB for each test series (flyover, approach, or takeoff). This, in effect, admits to a permissible 3dB data variation due to combined uncorrectable causes. It would therefore be prudent for a manufacturer to allow a 3dB margin between design target and allowable noise limit just to account for test and measurement variability.

V - EFFECT OF PREDICTION ACCURACY ON COST

Table I, which compares predicted and measured EPNL's indicates cases of both overprediction and underprediction. The impact of both of these types of prediction inaccuracies can most easily be seen by the examples of Table II applied to the level flyover case.

TABLE II NOISE REDUCTION REQUIREMENTS

	BO-105	CH-47C
Gross Weight (lbs.)	5070	40,654
FAR 36 Limit	89.5 EPNdB	98.6 EPNdB
Prediction		
Level	94.5	106.3
Reduction Required	5.0	7.7
Configuration Required	Mod 1*	Mod 1*
Measured		
Level	88.7	108.9
Reduction Required	0(-.8)	10.3
Configuration Required	Baseline*	Mod 2*

* Defined in Reference 1 and Appendix B

In the case of the BO-105 the overprediction would have resulted in unnecessary replacement of the baseline rotor and tail rotor gear box with the cost impacts shown in Figures 13 and 14.

The case of the CH-47C is more difficult to analyze. In this case, if no margin were taken, the aircraft selected by analytical prediction (Mod 1) would have failed to certify. As in the case of the BO-105, the configuration which would certify (Mod 2) requires a new advanced rotor and gear changes in the accessory drive system. The cost differences, shown in Figure 15 and 16, however, form what may be only a small part of the true costs. Failure to certify, on schedule, will usually have a severe effect on aircraft delivery thereby impacting sales and cash flow. If, for example, a new rotor system is required, but has not been fully developed, qualified, tested, and certified for performance, flying qualities, vibration, and structural integrity, the delay in schedule to full type certification would certainly be in excess of one year and frequently several years, while the cost of developing new rotors runs into millions of dollars. If the helicopter has competition from other manufacturers, the setback in the market could well prove catastrophic. For these reasons it is necessary to design the helicopter to a target noise level which is below the actual regulatory limit. In an oral presentation to the FAA Administrator, representatives of the helicopter industry stated that a 90% probability of successful certification would be required to make the required investment a prudent risk.

In order to develop a good basis for establishing the confidence limits on helicopter noise prediction considerably more comparisons of measured and predicted EPNL's are required than were done for this study. Even with these few cases, however, underpredictions of the order of 3 EPNdB for flyover and 5 EPNdB for approach were noted.

The Reference 1 report also examined the cost impact of noise reduction on several helicopters. Using that study as a basis it is possible to evaluate what the effect of designing those helicopters to lower noise level criteria would have

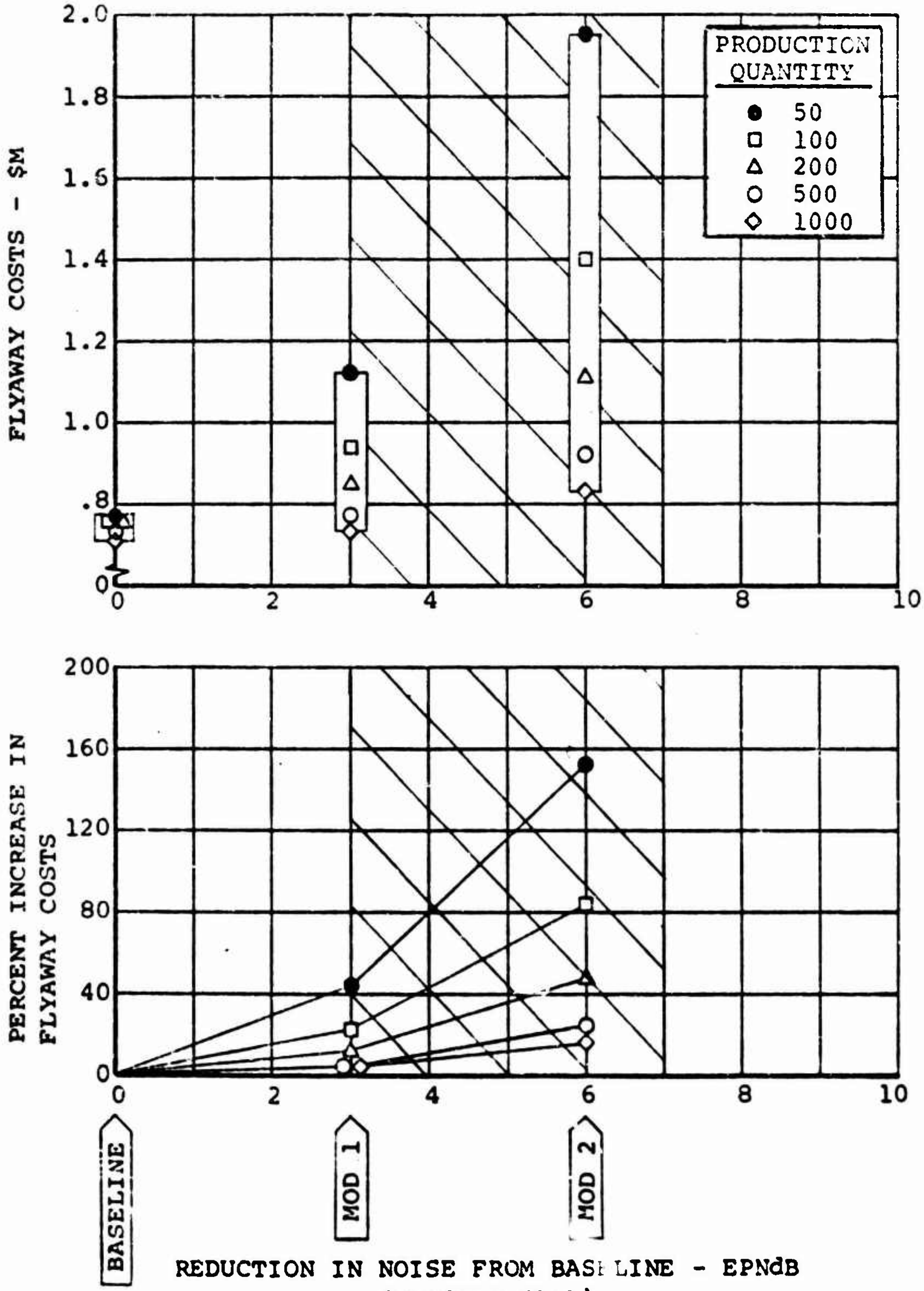


Figure 13. Effect of Configuration Changes on Flyaway Cost, BO-105 (Ref. 1)

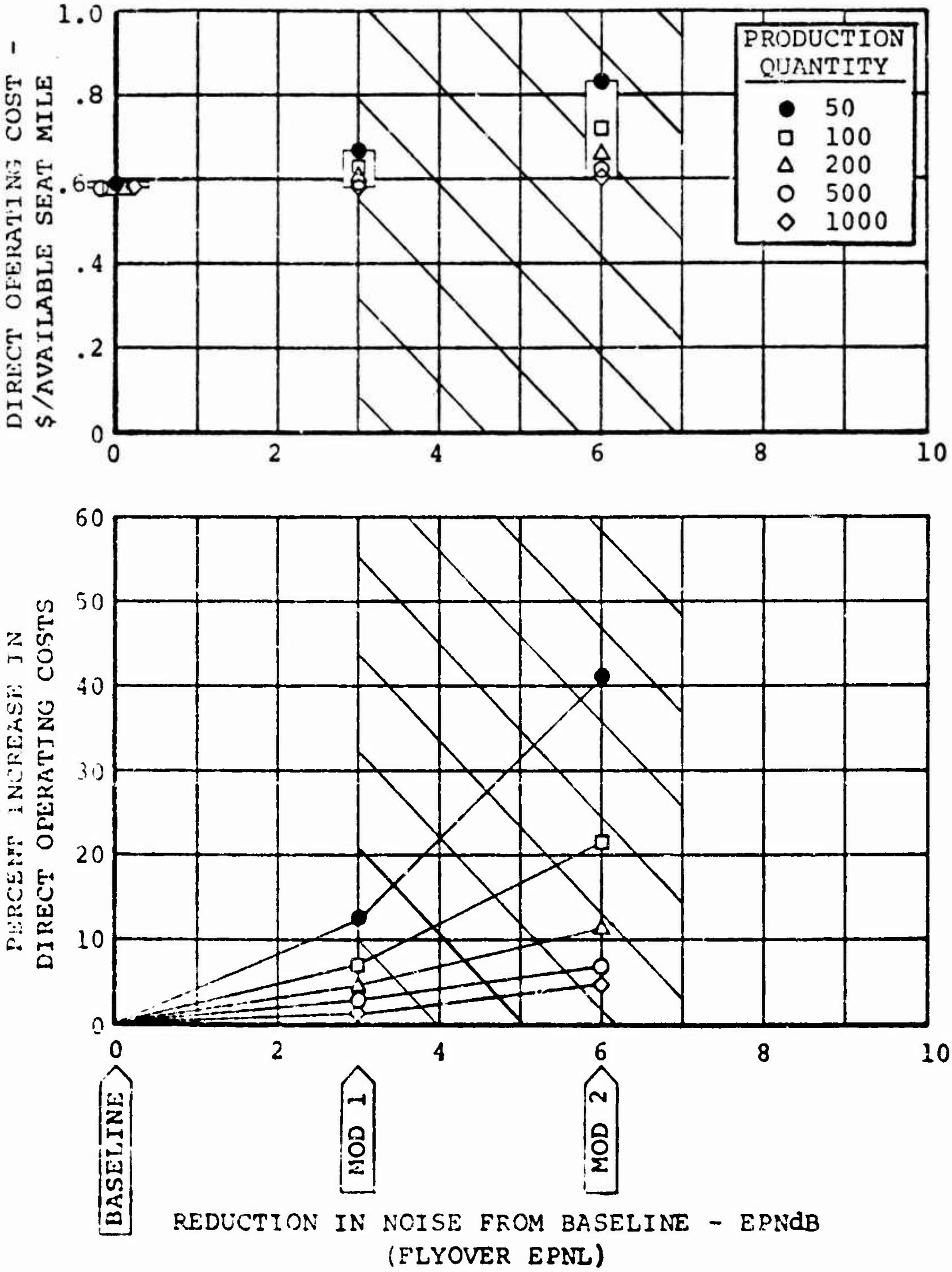


Figure 14. Effect of Configuration Changes on Direct Operating Cost, BO-105 (Ref. 1)

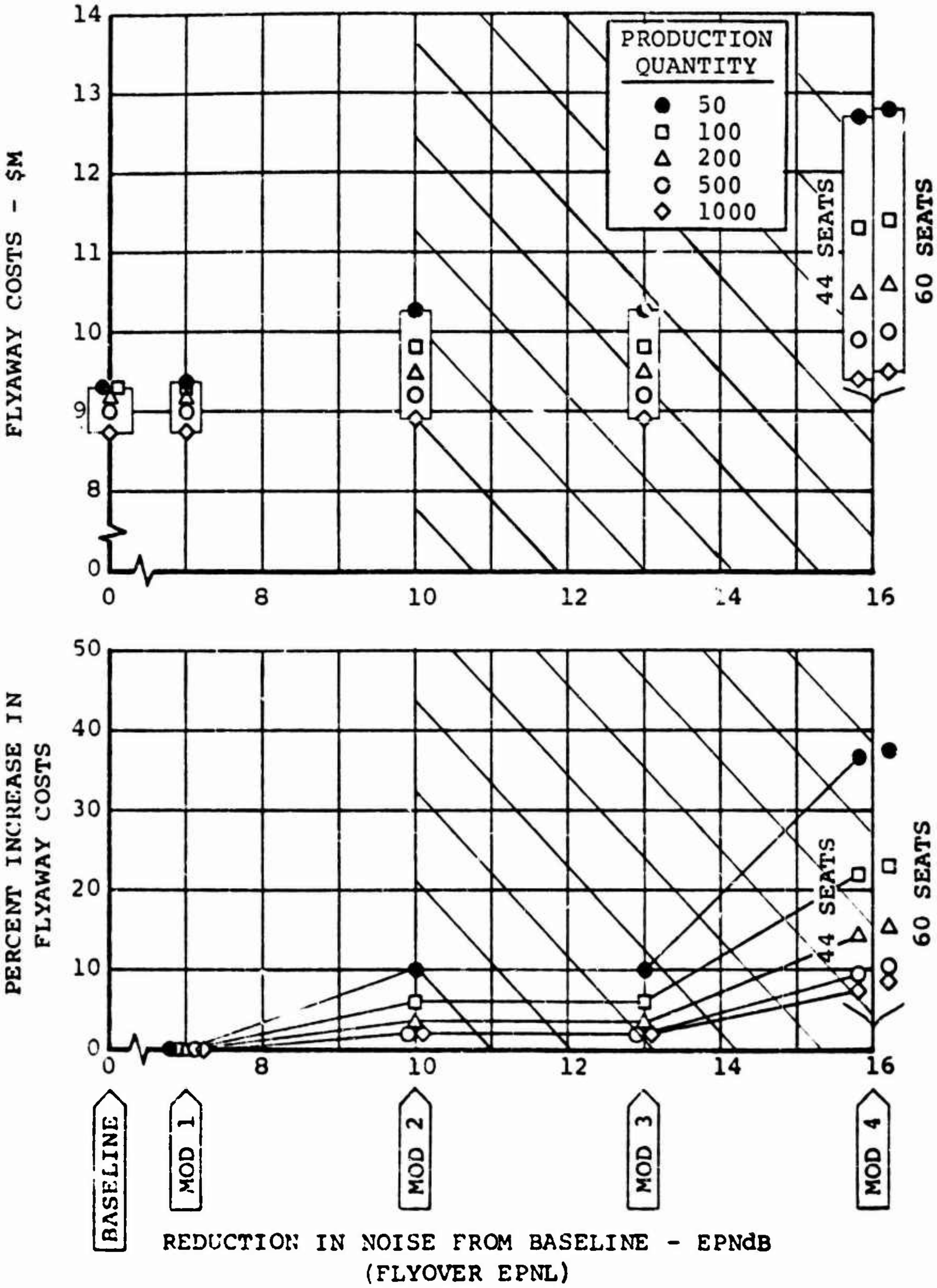


Figure 15. Effect of Configuration Changes on Flyaway Cost, CH-47 (Ref. 1)

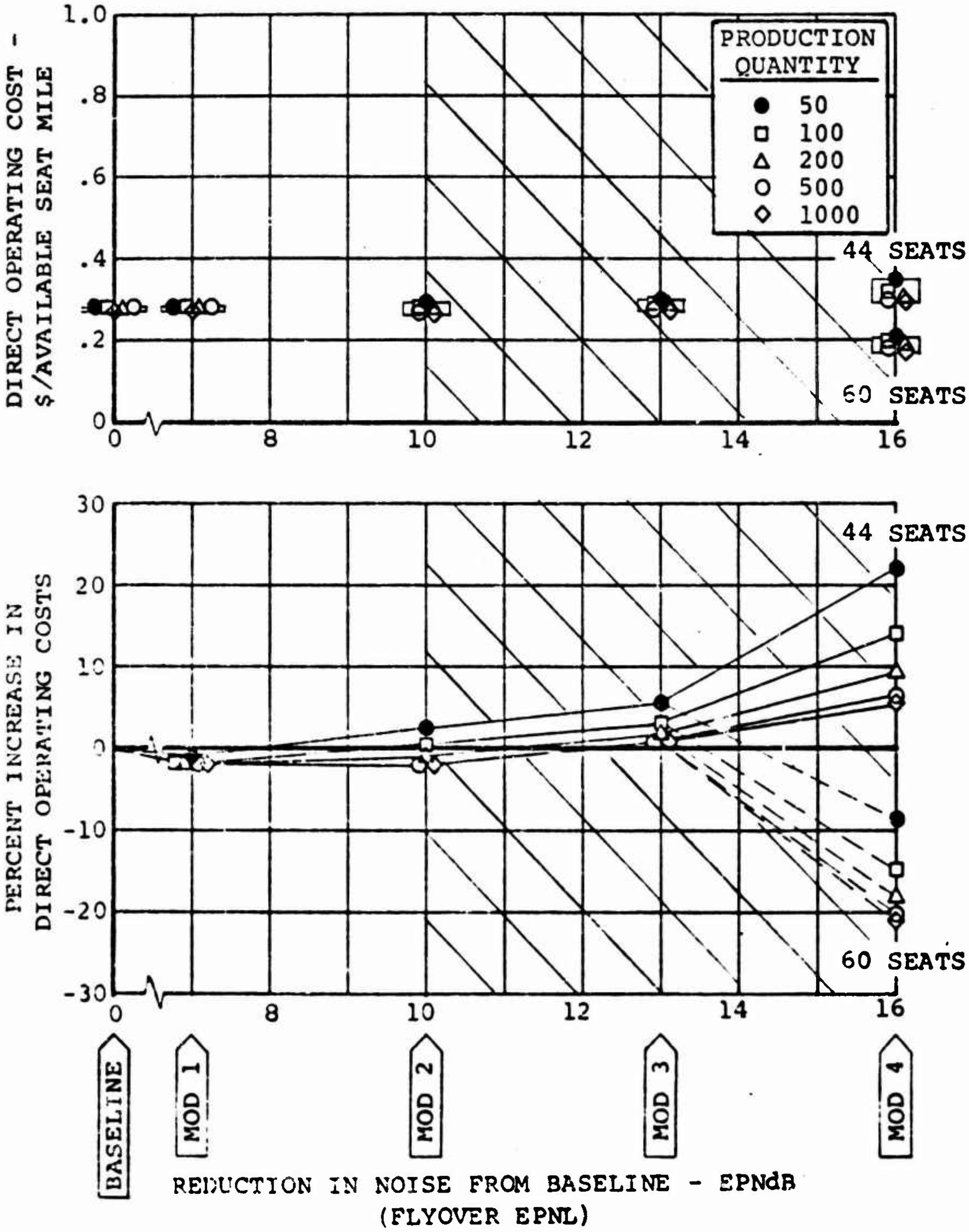


Figure 16. Effect of Configuration Changes on Direct Operating Cost, CH-47 (Ref. 1)

been. The results of the cost impact studies along with definitions of the aircraft configurations are included in Appendix B of this report. For purposes of this study the costs which would have been associated with designing the baseline aircraft to reduced target levels of 3dB, 6dB, and (in the case of the CH-47) 12dB were studied. The assumption in each case being that instead of the baseline aircraft the modified version which achieves the required reduction would have been required. These modifications are summarized in Table III.

TABLE III NOISE REDUCTION MODIFICATION

Required Reduction	BO-105	Helicopter Model Model 179	CH-47
3 EPNdB	Mod 1	Mod 1	-
6 EPNdB	Mod 2	Mod 3	Mod 1
12 EPNdB	--	--	Mod 3

* For definition of modifications see Reference 1 or Appendix B

The results of applying the cost impact data developed in Reference 1 to the configuration changes indicated in Table III are illustrated in Figure 17.

VI - CONCLUSIONS AND RECOMMENDATIONS

The study evaluated the ability to analytically predict helicopter noise and the impact which allowance for prediction accuracy has on helicopter costs. The sample of helicopters studied was very small and, while serving as specific examples, should not be used to derive general conclusions about the maximum range of prediction error or cost impact.

The effects of blade/vortex interaction on both main and tail rotors are particularly difficult to predict and when they occur can lead to severe underprediction of sound pressure level, tone correction, and duration correction.

It is recommended that this study be expanded by the addition of at least five other helicopters, mainly medium and large single rotor designs, for which measured data is available from testing which the FAA has already performed.

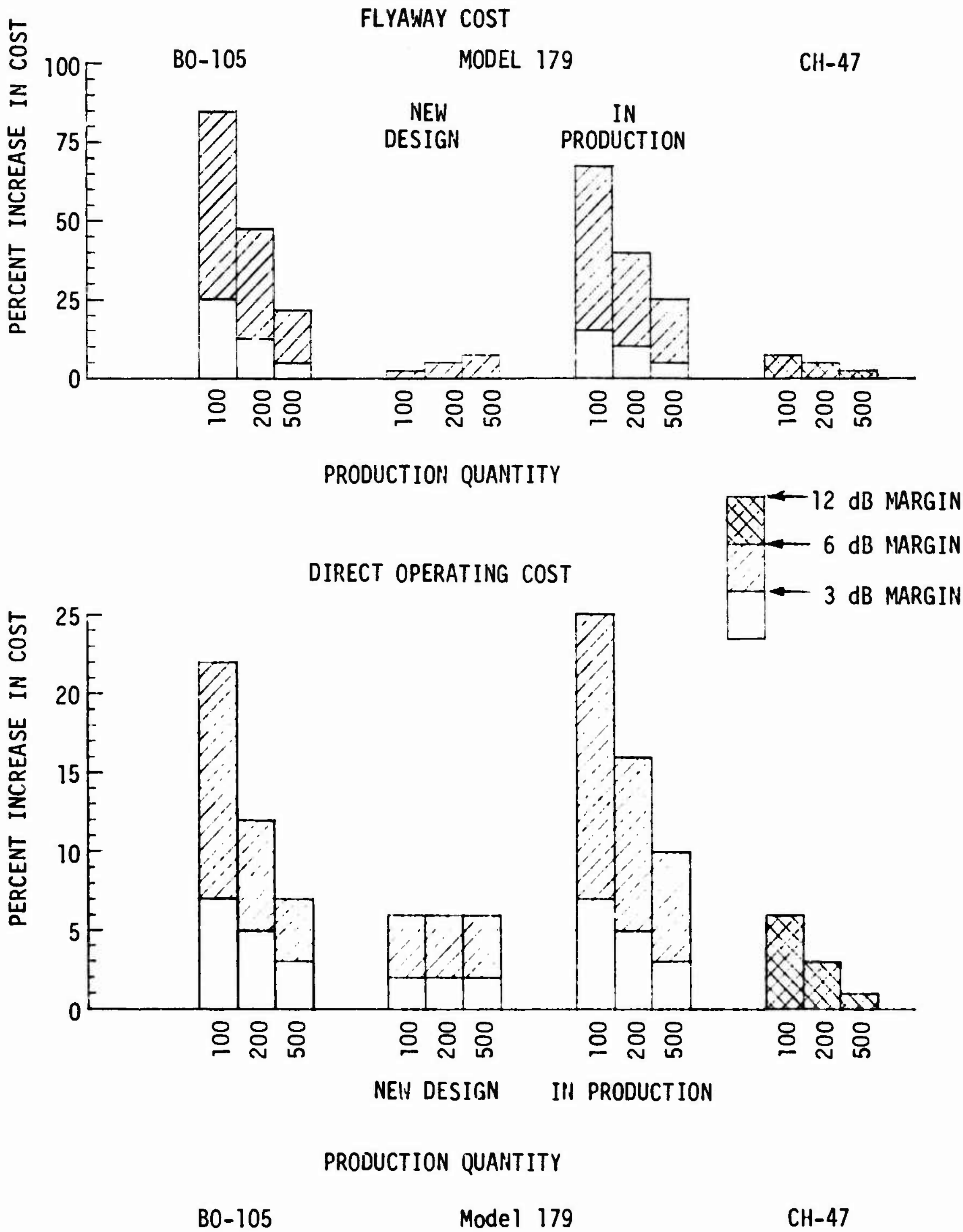


FIGURE 17. COSTS ASSOCIATED WITH DESIGNING TO REDUCED NOISE TARGET LEVELS

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1. Spencer, R. H., and Sternfeld, H., "Study of Cost/Benefit Tradeoffs Available in Helicopter Noise Technology Applications" Report No. FAA-EE-80-5, January 1980

2. Pegg, R. J., "A Summary and Evaluation of Semi-Empirical Methods for the Prediction of Helicopter Rotor Noise", NASA TM80200, December 1979

3. True, H. C. and Letty, R. M., "Helicopter Noise Measurements Data Report, Volume 11", Report No. FAA-RD-77-57, 11 April 1977

4. "Noise Standards for Helicopters in the Normal, Transport, and Restricted Categories", Notice of Proposed Rule Making No. 79-13, Federal Register, Vol. 44, No. 140, July 19, 1979

5. "Noise Standards: Aircraft Type and Airworthiness Certification", Federal Aviation Regulations Part 36 Change 12, January 15, 1979

APPENDIX A

ROTOR NOISE PREDICTION METHODOLOGY

The components of rotor noise calculated for the prediction of helicopter flyover acoustic signatures were (1) rotational, (2) broadband, (3) thickness, (4) compressibility, and (5) interaction noise. The first two of these methods had been previously programmed for machine computation and cases were run for all helicopters in the study.

Elements (3), (4) and (5) were calculated by hand from methods suggested by Pegg (Reference 2). Pegg reduced the computation complexity of the equations developed by several researchers in rotor acoustics. These elements were included, as appropriate, and summed with the rotational and broadband components to obtain estimates of the total flyover signature. The following section presents a synopsis of the equations adopted for use in this program.

Rotational Noise - The theory for this component of rotor noise was developed by Lowson and Ollerhead (6) and it forms the basis for the calculations of this element of rotor noise used in this program. Several assumptions were made to the original expression to permit a closed form solution:

$$C_n = \sum_{\lambda=o}^{\infty} K \cdot \frac{T}{Rr\ \lambda k} \left\{ (10nM \sin \theta) J_1' - J_2' + \left(\frac{nM}{R} \cos \theta\right) J_3' \right\}$$

C_n	amplitude of nth sound harmonic at specified field point
λ	air loading harmonic number
K	constant
r	distance between rotor center and field point
n=mB	harmonic number x number of blades
M	rotational Mach number
R	radius of action of blade forces
θ	angle between disc plane and field point
J_i'	complex collection of Bessel functions of argument ($nM \cos \theta$)
$C_{\lambda T}, C_{\lambda D}, C_{\lambda C}$	thrust, drag, radial force harmonic coefficients
k	loading power law exponent
T	thrust

(6) Lowson, M. V., and Ollerhead, J. B., "Studies of Helicopter Rotor Noise", USAAVLABS TR 68-60, January 1969.

For this study, it was assumed that the thrust, drag and radial force components were randomized with respect to phase, that the ratio of the magnitude of the components ($C_{\lambda T}$, $C_{\lambda D}$, $C_{\lambda C}$) were 10:1:1, respectively, and that the harmonic airload power law constant (k) was 1.8 including the $\lambda 0.5$ term due to random phasing effects.

Broadband Noise

The broadband noise equation used for this program was based on the work of Lowson (7), Hubbard (8), Schlegel (9) and Munch (10). It was further modified to reflect an observed dependence on average lift coefficient. The spectrum peak frequency was calculated from

$$fp = -240 \log T + 0.746 V_t + 786$$

The spectral content of broadband noise is shown in Figure A-1. One-third octave band sound pressure levels were then determined from the following equation based on rotor blades having constant chord, thickness and airfoil section along the radius:

$$SPL_{1/3} = 20 \log \frac{V_t{}^3}{r} + 10 \log A_b \, (\cos^2\theta + 0.1) + S_{1/3} + f(\bar{C}_\ell) - 53.3$$

where

SPL_j	sound pressure level in the jth 1/3 octave band
fp	peak frequency
T	thrust
V_t	tip speed
A_b	blade area
θ	angle between disc plane and field coordinate
r	distance to field coordinate
$S_{1/3}$	1/3 octave band correction from Fig. A-1
$\bar{C}_\ell$	average lift coefficient

(7) Lowson, M. V., "Thoughts on Broad Band Noise Radiation by a Helicopter", Wyle Laboratories WR 68-20, 1968.

(8) Hubbard, H. H., "Propeller Noise Charts for Transport Airplanes", NACA TN 2968.

(9) Schlegel, R., King, R. J., and Mull, H., "Helicopter Rotor Noise Generation and Propagation", USAAVLABS Technical Report 66-4, October 1966.

(10) Munch, C. L., "Prediction of V/STOL Noise for Applications to Community Noise Exposure", DOT-TSC-OST-73-19, May 1973.

Thickness Noise - Calculation of thickness noise was based on the theoretical analysis developed by Hawkings and Lowson (11). The following equation presents the harmonic sound pressure for thickness noise valid for hovering conditons:

$$p_{mB} = \frac{4}{\sqrt{2}\pi} M_t^2 \rho C_o^2 \left(\frac{R}{r}\right)\left(\frac{t}{c}\right)\int_1^\infty \frac{1}{\xi^4} \left(\frac{\sin nk\xi}{nk\xi} - \cos nk\xi\right) J_n\left(\frac{nM_t}{\xi}\cos\theta\right) d\xi$$

where:

p_{mB}	sound pressure level in harmonic mB
M_t	rotational tip Mach number
ρ	air density
C_o	speed of sound in air
R	rotor radius
r	distance between rotor center and field point
t	blade thickness
c	blade chord
ξ	$\frac{R_t}{R}$
n	mB
m	sound harmonic number
B	number of blades
k	$c/2R_t$, slenderness ratio
J_n	Bessel function of order n and argument $\left(\frac{nM_t}{\xi}\cos\theta\right)$

For estimating thickness noise levels, Pegg reduced the above expression to,

$$SPL_t = 40\log M_t + 20\log\frac{t}{c} + 20\log B + 20\log\frac{R_t}{r} + \Delta SPL_t - 0.9$$

where ΔSPL_t represents an evaluation of

$$\int_1^\infty \frac{1}{\xi^4}\left(\frac{\sin nk\xi}{nk\xi} - \cos nk\xi\right) J_n\left(\frac{n M_t}{\xi}\cos\theta\right) d\xi$$

for a matrix of values of M_t, θ and k.

(11) Hawkings, D. L., and Lowson, M. V., "Tone Noise of High Speed Rotors", Second Aero-Acoustics Conference, Hampton, Virginia, March 24-26, 1975, AIAA Paper 75-450.

Compressibility-Induced Profile Drag Noise - Prediction of compressibility noise is based on the work of Lowson and Ollerhead as modified by Arndt and Borgmann (Reference 12) who related the effect of compressibility drag on impulsive noise in the following expression,

$$P_{mB} = \frac{mB\bar{C}_{D_0}}{4\pi^2\sqrt{2}} \frac{\Delta\psi}{\pi} \frac{R}{R_e} \frac{C}{r} \rho C_o^2 \sum_{j=-\infty}^{+\infty} \left(1-\frac{j}{mB}\right)\beta j \; J_{(mB-j)}(mBM_e \sin\theta).$$

Pegg has derived a simplified form for the solution to this, assuming a drag divergence Mach number of M_{dd}=0.8.

$$SPL_{mB} = 20 \log \frac{R}{r} + 20 \log \left[(M_e-0.8) \frac{C}{R}\right] + \Delta SPL_c - 21.6$$

where

M_e effective Mach number, $\dfrac{M_T}{1-M_f\cos\theta}$

ΔSPL_c evaluation of the summation on the right side of the first equation

$\bar{C}_{D_0}$ profile drag coefficient

$\Delta\psi$ incremental azimuth angle where blade section M > 0.8.

β_j Fourier coefficients in blade torque loading

j summation index

Blade/Vortex Interaction - The component of interaction noise resulting from the intersection of trailed tip vortex filaments and rotor blades was estimated using a method proposed by Wright (Reference 13),

where $$P_{mB} = \left(\frac{\Delta L}{L_0} E \rho_w\right) K_T \, mB \, X_S$$

E number of interactions per revolution

ρ_w load solidity (fraction of the effective disk annulus occupied by the unsteady loading region

$\dfrac{\Delta L}{L_o}$ fractional steady load change per blade

(12) Arndt, R. E. and Borgman, D. C., "Noise Reduction from Helicopter Rotors Operating at High Tip Mach Number", American Helicopter Society, 26 Annual Forum, June 1970.

(13) Wright, S. E., "Discrete Radiation From Rotating Periodic Sources", Journal Sound and Vibration (1971) 17(4) 437-498.

K_T thrust constant

X_s blade loading spectrum function,

$$= \frac{\sin\pi(ft_o-1)}{4(ft_o-1)} - \frac{\sin\pi(ft_o+1)}{4(ft_o+1)}$$

(for sine wave pulse profile)

ft_o $SE\rho_w$, (non-dimensional parameter)

S blade loading harmonic number

The simplified expression for interaction noise takes the form,

$$SPL_{mB} = 20 \log \frac{\cos\theta}{rC_o} + 20 \log \frac{\Delta L}{L_o} + 20 \log T\Omega + 20 \log (\chi_s \frac{mB\Delta\psi}{\psi o}) + 120.6$$

where

θ angle between disc plane and observer

T rotor thrust

Ω rotational speed

$\Delta\psi$ azimuthal range of load excursion

ψ_o azimuth at intersection

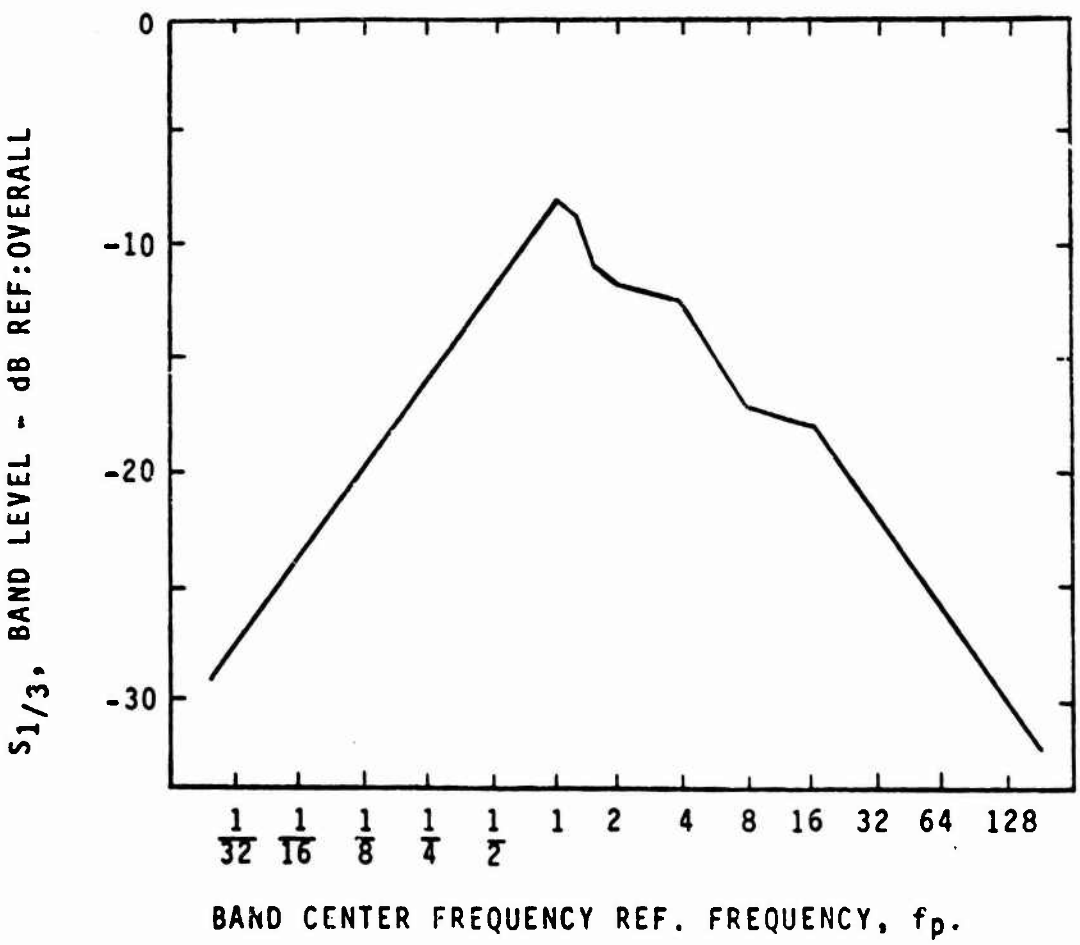

FIGURE A-1 ROTOR BROADBAND NOISE EMPIRICAL SPECTRUM

APPENDIX B

DEFINITIONS OF CONFIGURATION MODIFICATIONS AND COST DATA FROM REFERENCE 1

Table B-1 BO-105 Configuration Changes

	Baseline	Modification 1	Modification 2
MAIN ROTOR			
V_t (ft/sec)	716	716	700
RPM	425	425	415
No. of Blades	4	4	4
Airfoil	23012	23012	23012
Chord (ft)	0.883	0.883	0.971
TAIL ROTOR			
V_t (ft/sec)	722	702	702
RPM	2224	2162	2162
No. of Blades	2	2	2
Airfoil	0012	Advanced airfoil, higher L/D, increased twist.	Same as Mod. 1 plus 10% increase in solidity.
Chord (ft)	0.58	0.58	0.61
Flyover EPNL	89.5	86.5	83.5
Dynamic System	Basic	New T/R speed, T/R gearbox.	M/R transmission acoustical treatment.
Airframe	Basic	Basic	Tail Rotor offset laterally by 1.77 ft.
Powerplant	Allison 250-C20	Allison 250-C20	Allison 250-C20
Weight Change (lb)	-	1.5	56.5

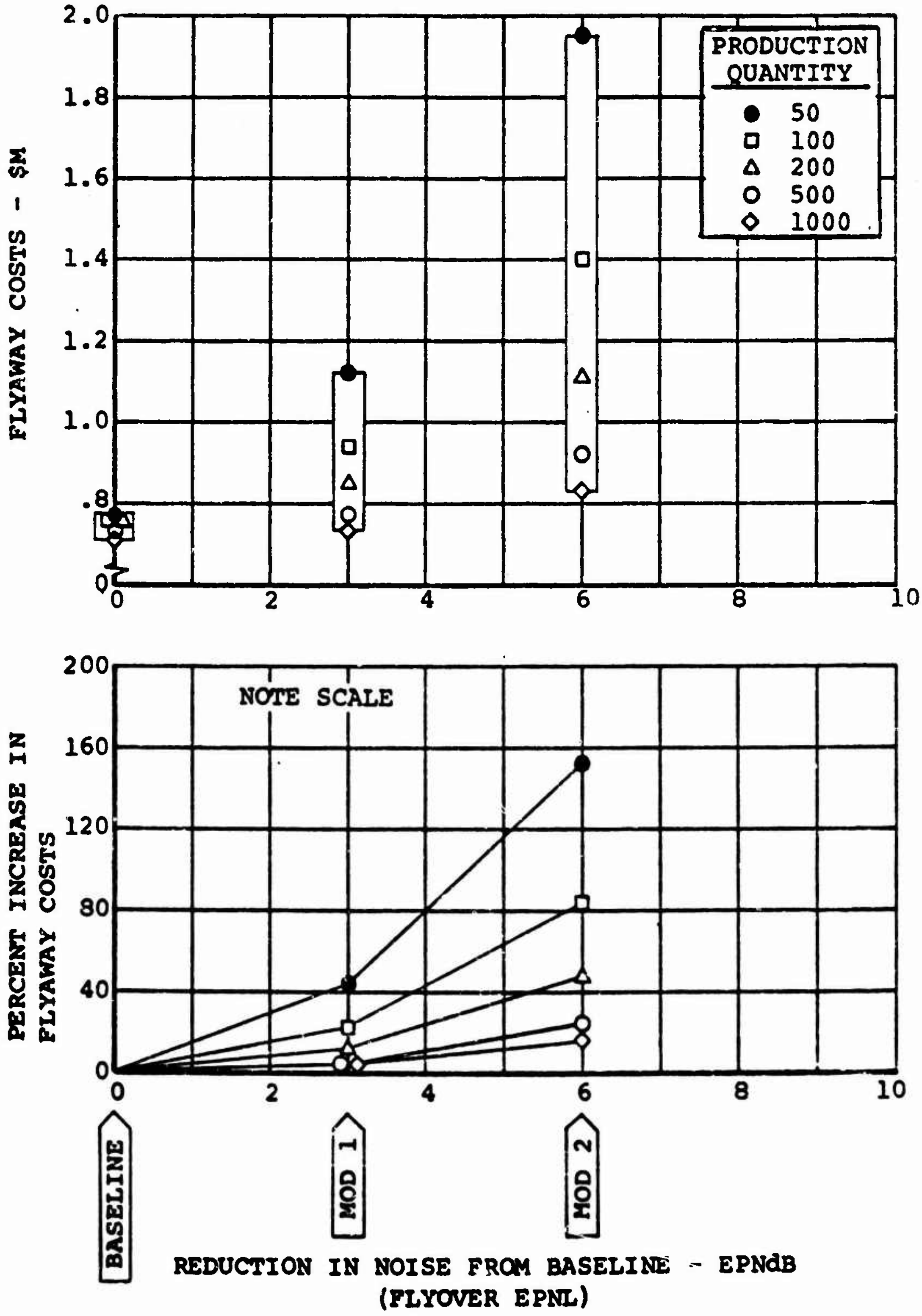

Figure B1. Effect of Configuration Changes on Flyaway Cost, BO-105

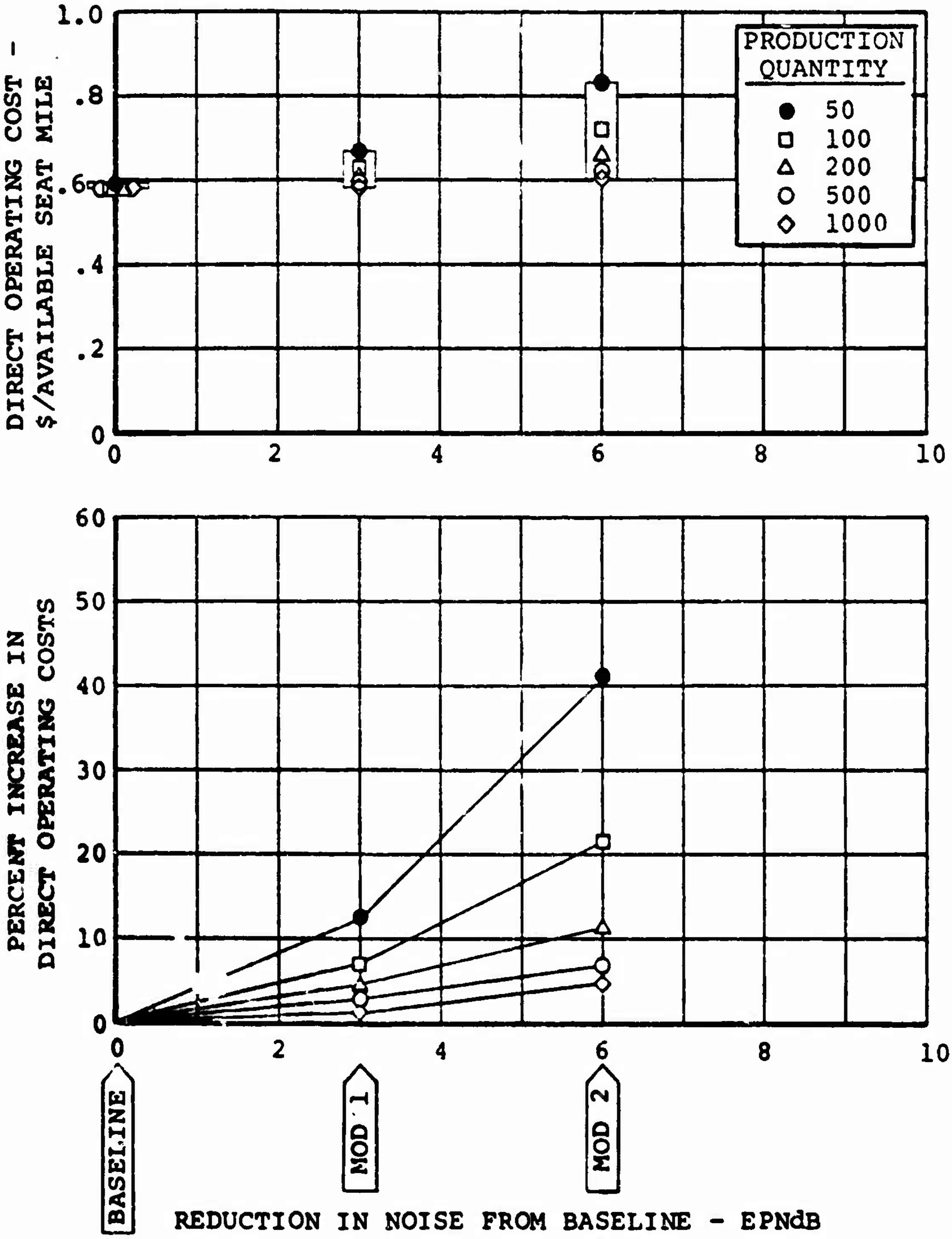

Figure B2. Effect of Configuration Changes on Direct Operating Cost, BO-105

Table B-2 Model 179 Configuration Changes

	Baseline	Modification 1	Modification 2	Modification 3
MAIN ROTOR				
V_t (ft/sec)	734	718	715	694
RPM	286	280	278	270
No. of Blades	4	4	4	4
Airfoil	VR-7,8,9	VR-7,8,9	VR-7,8,9	VR-7,8,9
Chord	23.0 In.	23.0 In.	24.9 In.	24.9 In.
TAIL ROTOR				
V_t (ft/sec)	690	668	665	654
RPM	1296	1256	1250	1229
No. of Blades	4	4	4	4
Airfoil	VR-7,8	VR-7,8 Increased twist, modified tip.	VR-7,8 Increased twist, modified tip.	VR-7,8 Increased twist, modified tip.
Chord	0.73 ft	0.73 ft	0.80 ft	0.80 ft
Flyover EPNL	98	95	94.5	91
Dynamic System	Basic	New T/R Gearbox	New T/R Gearbox	New T/R Gearbox
Airframe	Basic	Basic	Basic	Offset Tail Rotor
Powerplant	GE CT 7-1	GE CT 7-1	GE CT 7-1	GE CT 7-1
Weight Change (lb)	-	+52 lb	+111 lb	+191 lb

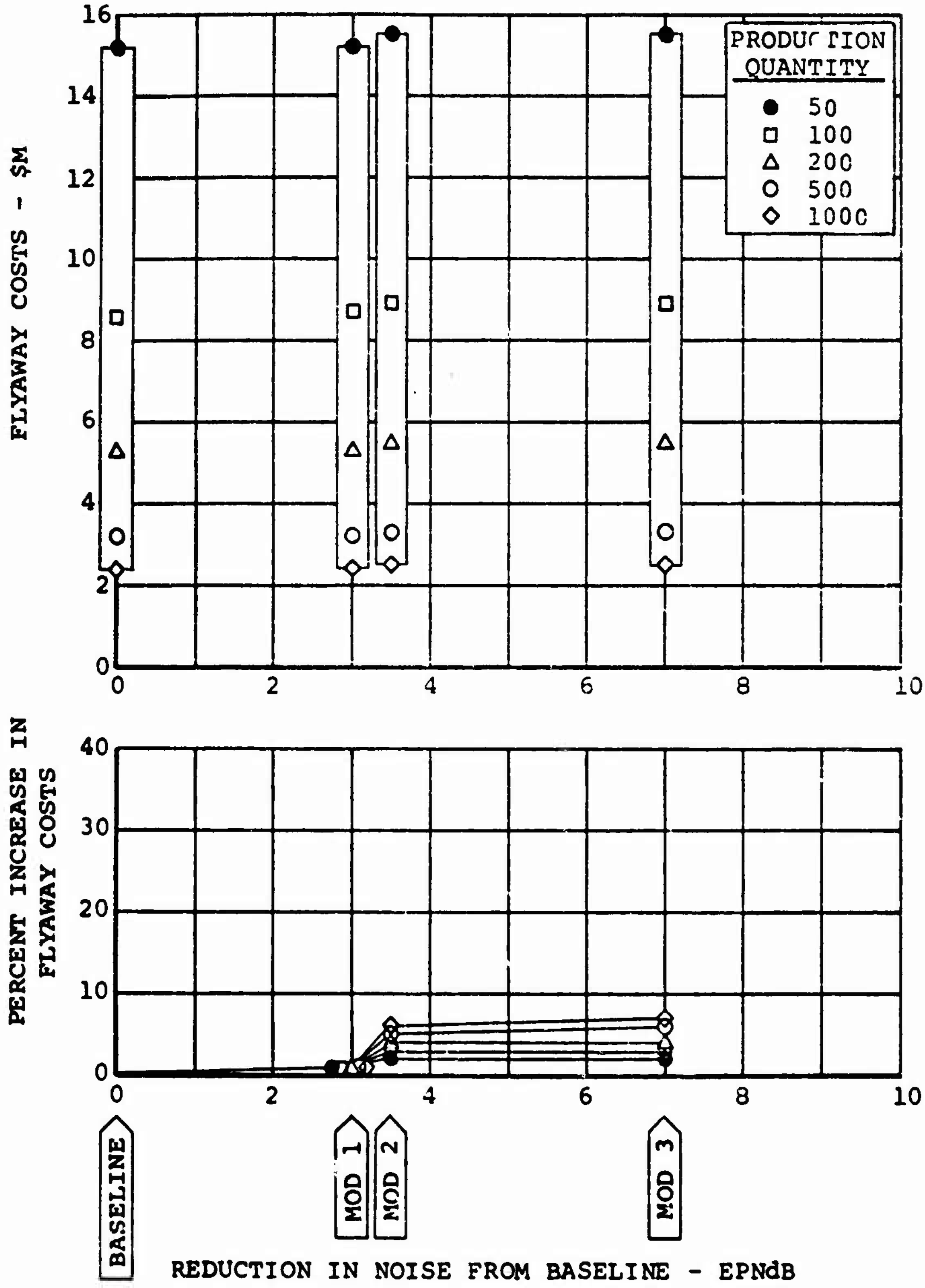

Figure B3. Effect of Configuration Changes on Flyaway Cost, Model 179 "New" Helicopter

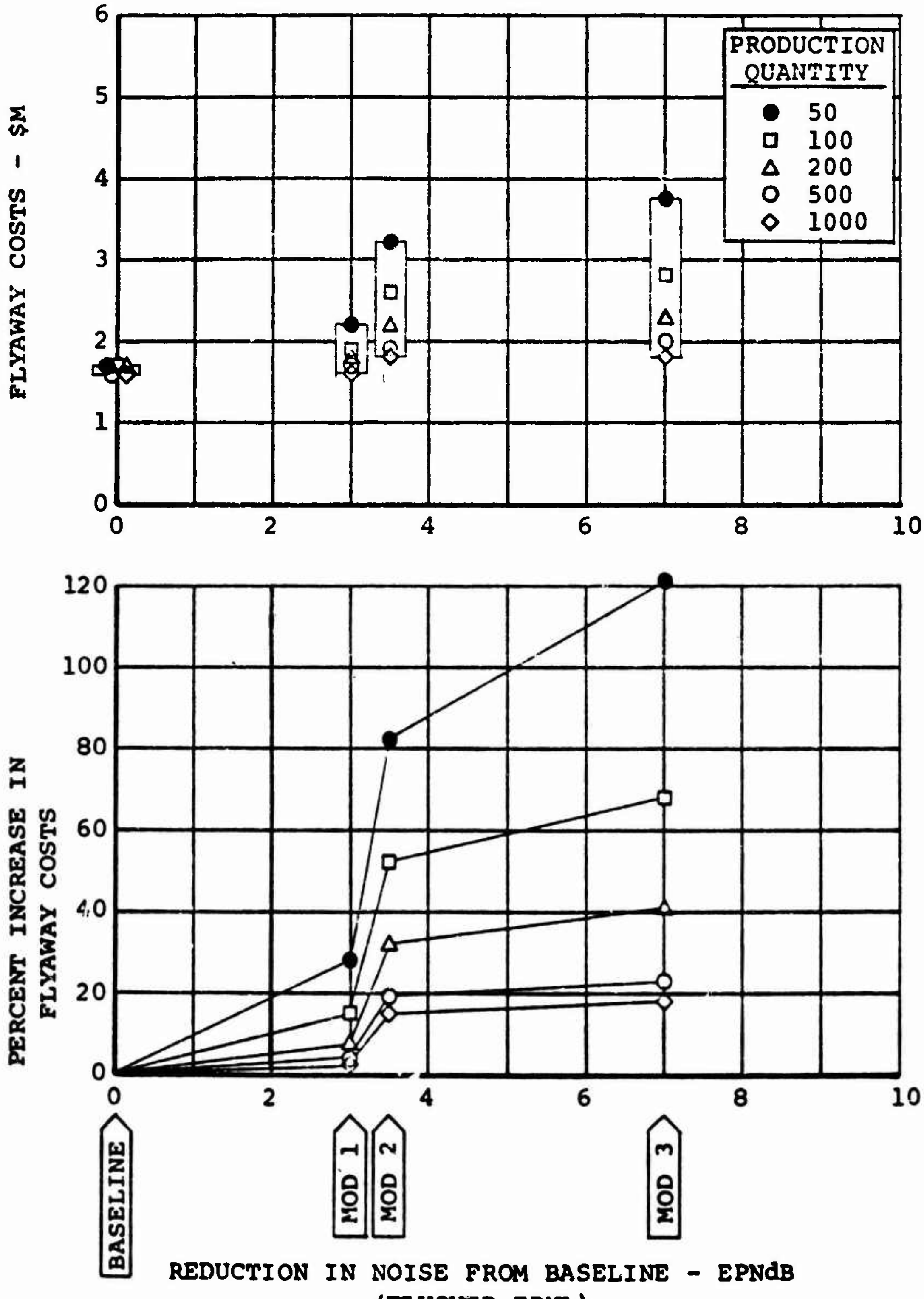

Figure B4. Effect of Configuration Changes on Flyaway Cost, Model 179 'In-Production'

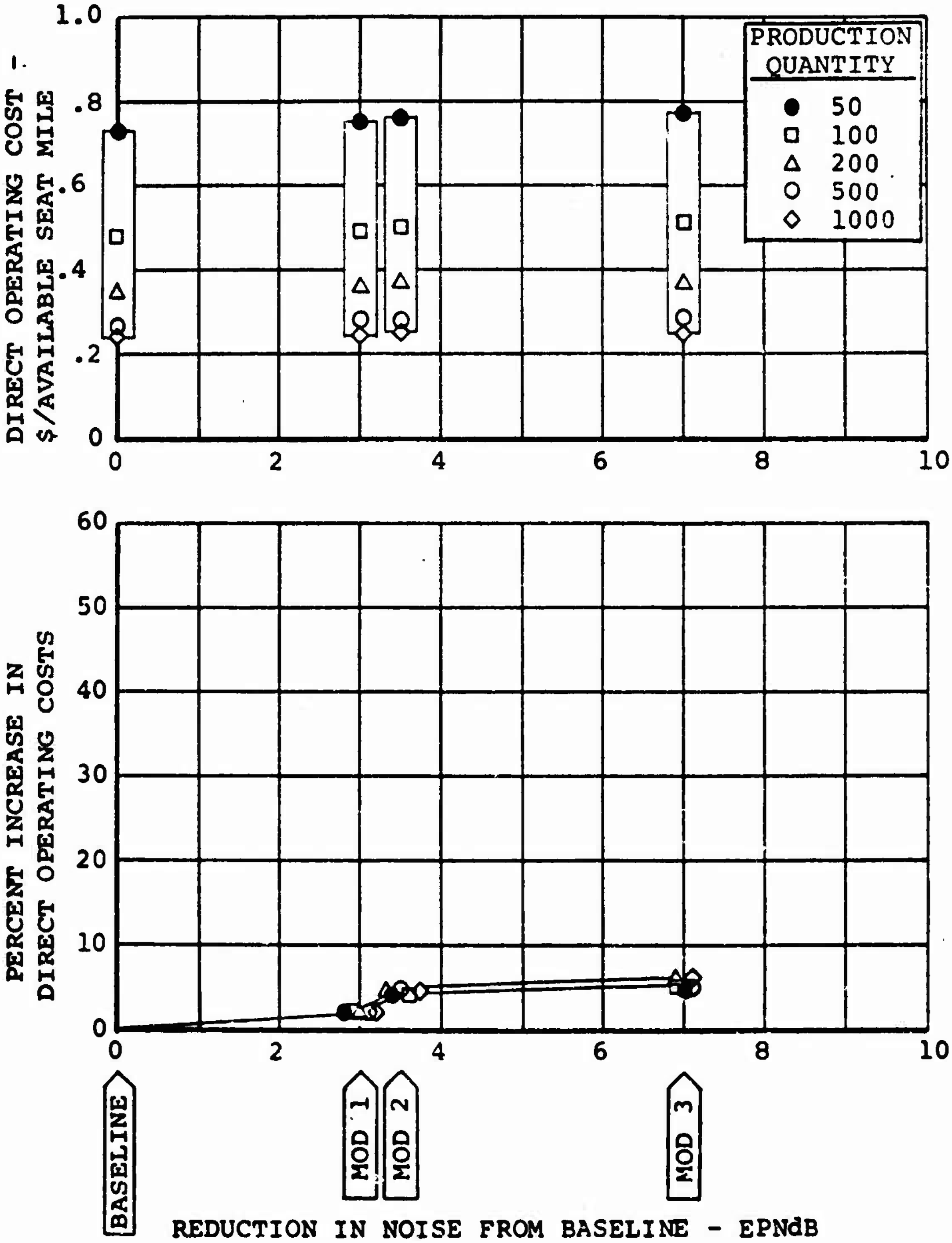

Figure B5. Effect of Configuration Changes on Direct Operating Cost, Model 179 'New' Helicopter

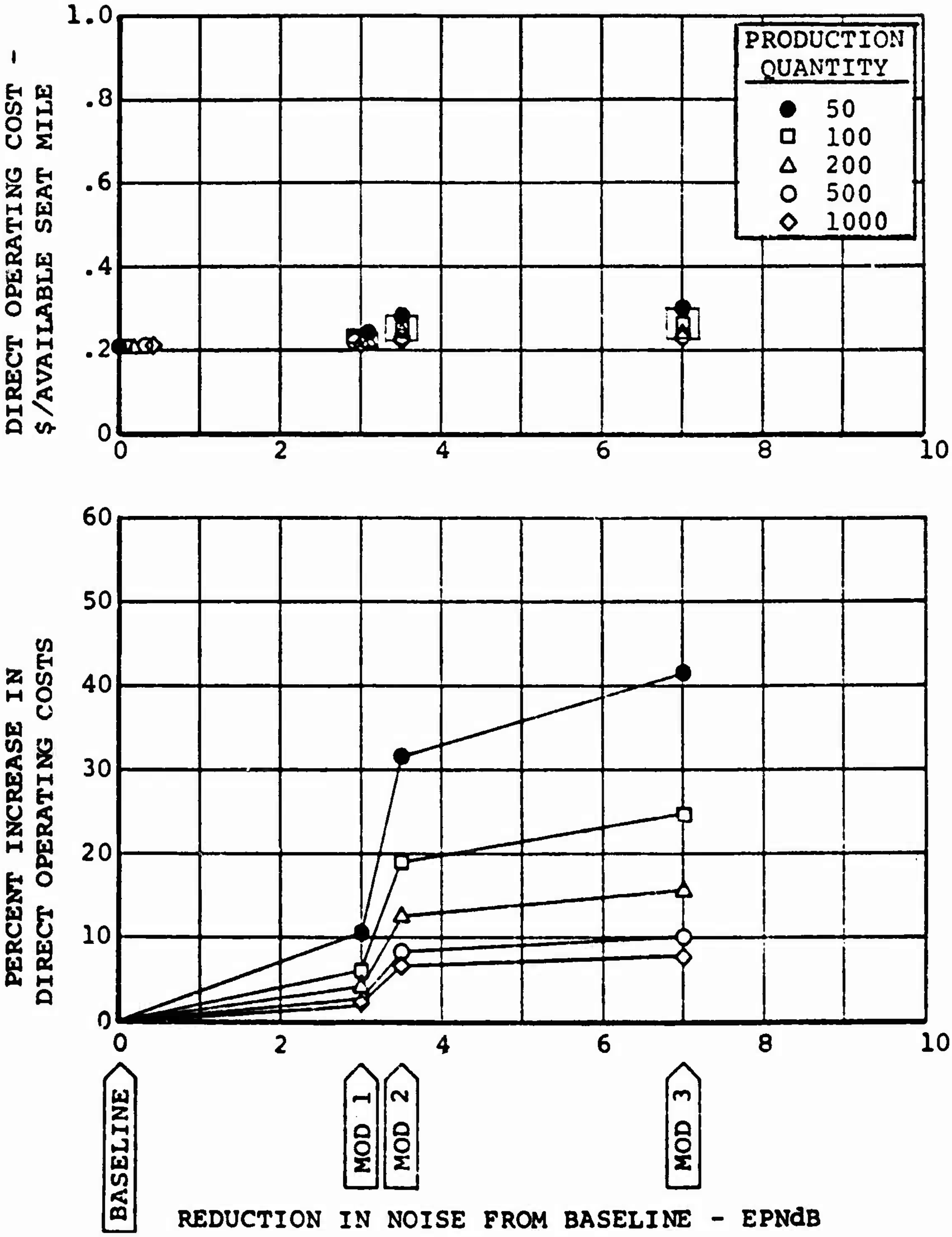

Figure B6. Effect of Configuration Changes on Direct Operating Cost, Model 179 'In-Production' Helicopter

Table B-3 CH-47 Configuration Changes

	Baseline	Modification 1	Modification 2	Modification 3	Modification 4
V_t (ft/sec)	770	707	707	675	691
RPM	245	225	225	215	220
No. of Blades	3	3	3	3	4
Airfoil	23010-1.58	23010-1.58	VR-7,8	VR-7,8	VR-7,8
Chord (ft)	2.10	2.10	2.67	2.67	2.67
Radius (ft)	30.0	30.0	30.0	30.0	30.0
Flyover EPNL	106	99	96	93	90
Dynamic System	Basic	Basic	New gear set, accessory drive	New gear set, accessory drive	New gear set, accessory drive, new aft rotor shaft
Airframe	Basic	Basic	Basic	Basic	120 in. fuselage stretch 20 in. aft pylon plug
Powerplant	AL 5512	AL 5512	AL 5512	AL 5512	AL 5512
Weight Change	-	-	+251	+251	+3490

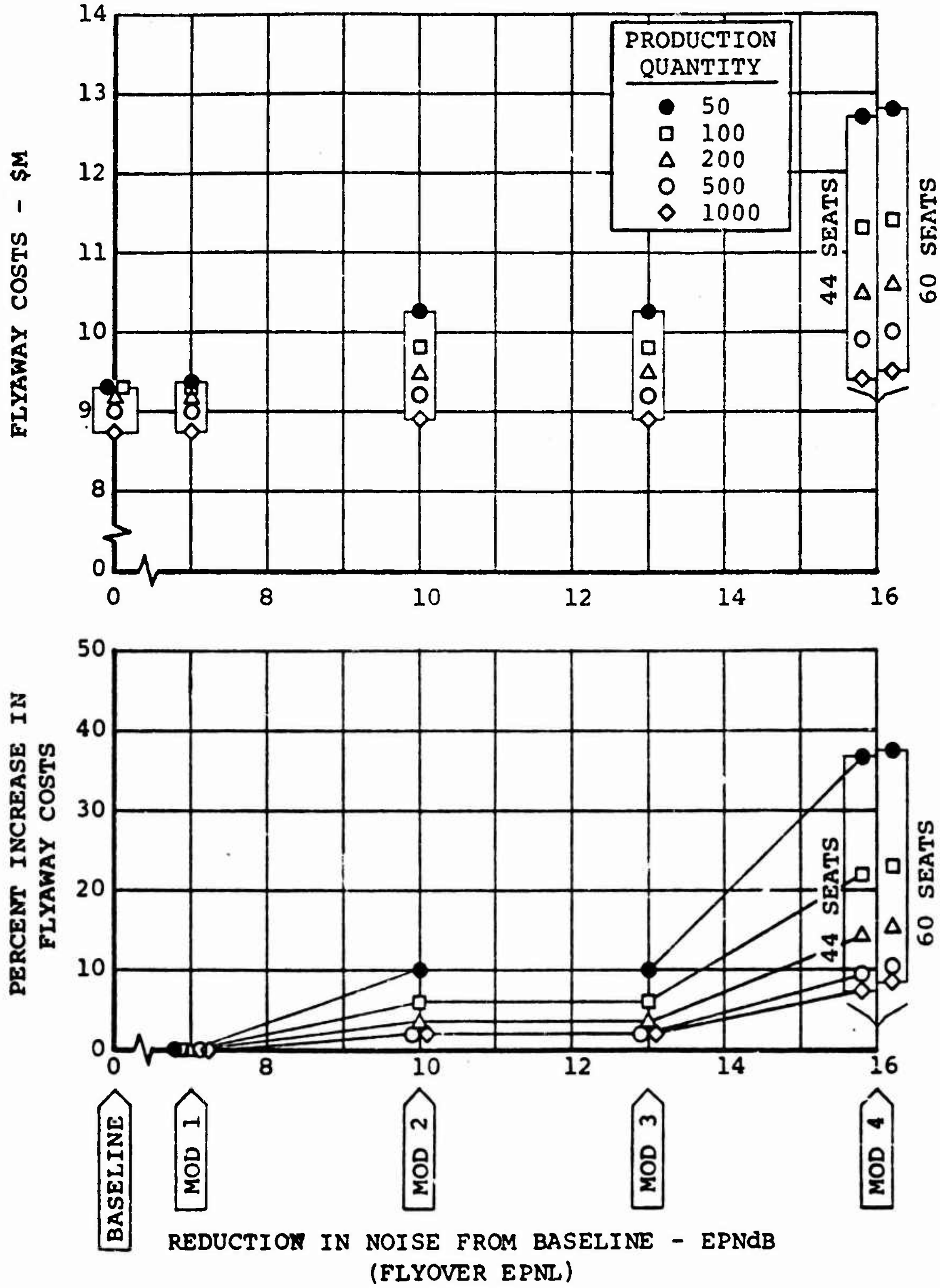

Figure B7. Effect of Configuration Changes on Flyaway Cost, CH-47

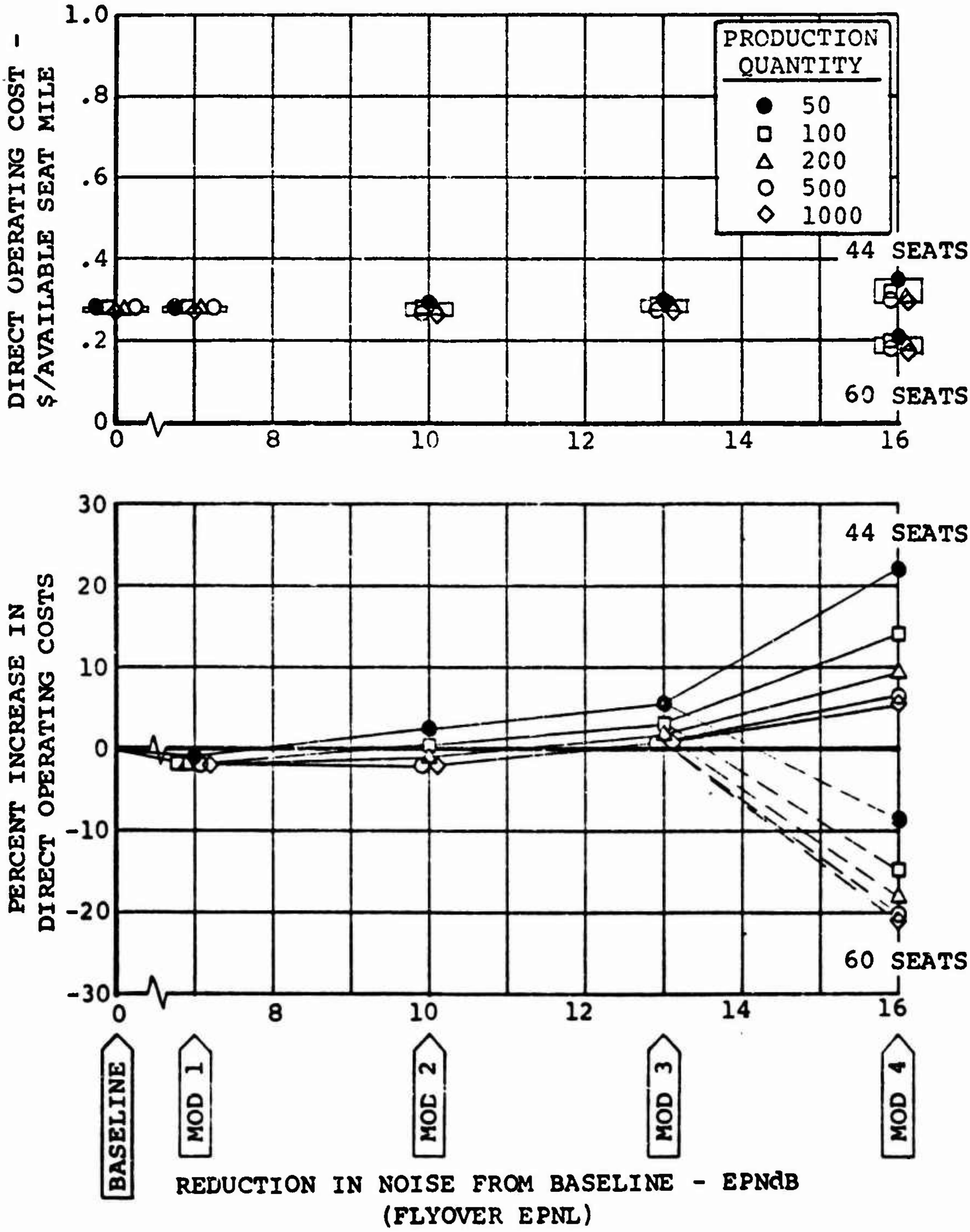

Figure B8. Effect of Configuration Changes on Direct Operating Cost, CH-47